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ABSTRACT

This issue of Exploratorium Magazine focuses on the topic robotics. It explains how to make a vibrating robotic bug and features articles on robots. Contents include: (1) "Where Robot Mice and Robot Men Run Round in Robot Towns" (Ray Bradbury); (2) "Robots at Work" (Jake Widman); (3) "Make a Vibrating Robotic Bug" (Modesto Tamez); (4) "The Robot in the Mirror" (Hugh McDonald); (5) "Fragments" (Pearl Tesler); (6) "Bringing Up Baby" (Erica Klarreich); (7) "ARS Robotica" (Liisa Pine); and (8) "Race for the Robocup" (Beth Martin). (YDS)

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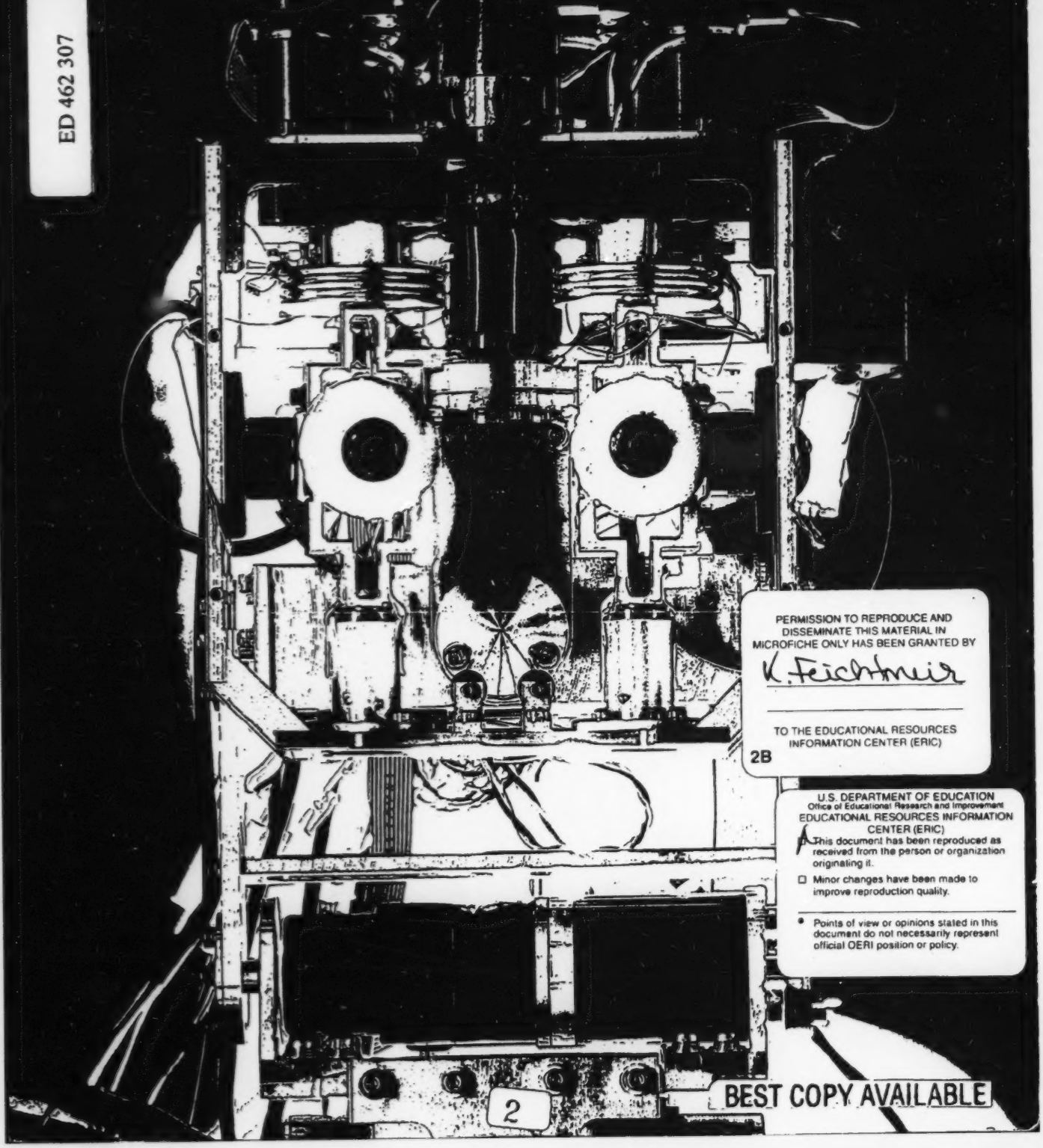

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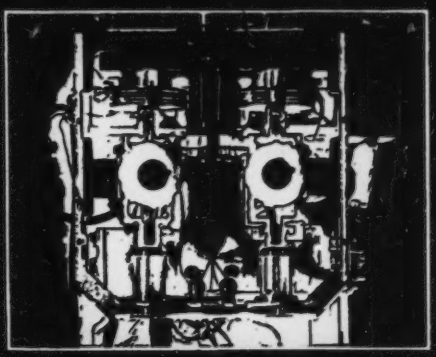

expl ratorium

Vol. 25 No. 1 Winter 2001/2002

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From the Director

Dear Friends,

Robotics enables us to accomplish tasks with unprecedented accuracy and safety, whether in daily life or while undertaking global security. We celebrate the wonders of robotics partly because the science and technology involved represent the achievement of the human mind.

Studying the human role in science—how people teach and learn, interact, and build communities of learners—will be a central effort of a major new initiative that we have just launched: the Center for Informal Learning and Science, led by the Exploratorium, the University of California at Santa Cruz, and King's College in London. The Exploratorium is a pioneer in developing programs that improve school-based ("formal") teaching through methods developed at "informal" science centers. Both UC Santa Cruz and King's College are recognized as two of the finest academies in the world, known for both their science programs and their excellence in science education.

The Center is the result of the Exploratorium's thirty-two-year history of working to bridge the gap between science centers, colleges of education, and local school districts. Our track record, and that of our partners, has garnered the Center a $10 million grant from the National Science Foundation over the next five years. We have already received a $300,000 matching grant from NEC Foundation of America to support using technology to expand the Center's impact, the first of what we hope will be widespread support for our work.

More importantly, we anticipate that the Center will have a profound impact on the way science is taught in the United States and abroad. The Center will offer graduate courses, research opportunities, and institutes for dozens of students each year, who in turn will form a new generation of education leaders working both in academia and at science centers worldwide.

The Center will create, in essence, a new professional field of museum educators, graduate students, doctoral candidates, and researchers, all working on ways to collaborate on improving science learning. A Ph.D. geneticist might decide to take coursework as a way to move from the lab into the teaching world. An education researcher might study how museum-based programs at the Science Museum of London support long-term student learning. A middle school teacher from the Midwest might take graduate courses that help her create a program for teachers at her local science museum. Or a young Monterey Bay Aquarium outreach worker might complete a certificate course that propels her into full-time study in marine biology. All of them will be connected through the Center, learning from each other and shaping the future of science education.

I trust that as a friend of the Exploratorium, you share in the excitement of knowing that the museum's impact on science education reaches a growing international audience.

Yours,

Goéry Delacôte
Executive Director

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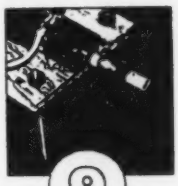
BE CAREFUL! The experiments in this publication were designed with safety and success in mind. But even the simplest activity or the most common materials can be harmful when mishandled or misused. Use common sense whenever you're exploring or experimenting.

Robots

Exploratorium Magazine
Winter 2001/2002

Robots at Work
by Jake Widman
From car factories to search-and-rescue operations, robots are helping get the job done.

Multi-Minirobots
by Louisa Dalton
In the world of robotics, bigger isn't necessarily better.



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by Modesto Tamez
Build a simple robot.

The Robot in the Mirror
by Hugh McDonald
What robots on the silver screen can tell us about ourselves.

Bringing Up Baby
by Erica Klarreich
Can robots learn like humans?

Ars Robotica
by Liisa Pine
Artists meet at the crossroads of art and science.

Race for the RoboCup
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Soccer-playing robots use teamwork to win the game.

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First Word

by Ray Bradbury

Where Robot Mice and Robot Men

They asked me where I'd choose to run, which favored? Ups? or Downs?
Where robot mice and men, I said, run round in robot towns.

But is that wise? for tin's a fool and iron has no thought!
Computer mice can find me facts and teach me what I'm not.

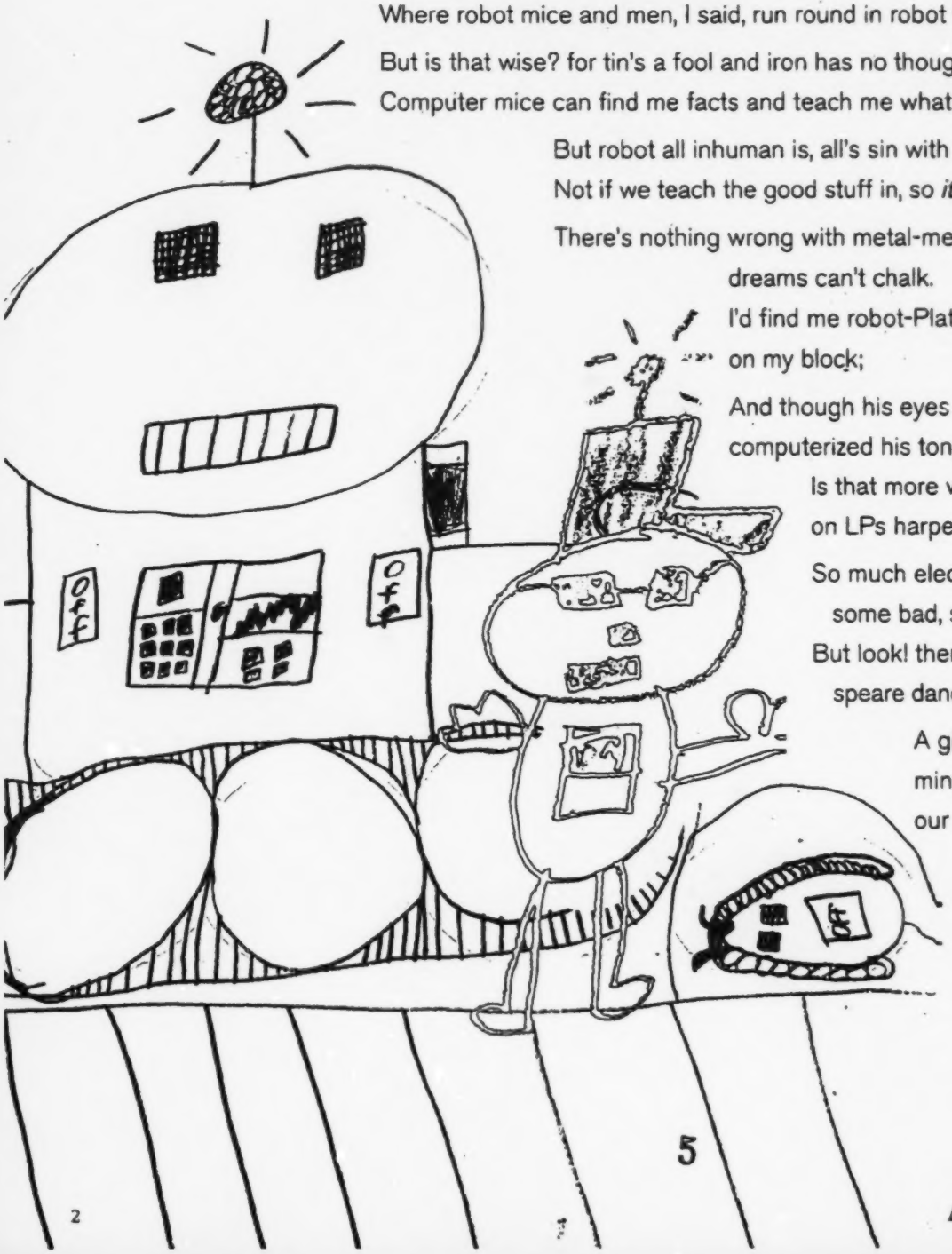
But robot all inhuman is, all's sin with cog and mesh.
Not if we teach the good stuff in, so *it* can teach our flesh.

There's nothing wrong with metal-men that better
dreams can't chalk.
I'd find me robot-Plato's cave if he lived
on my block;

And though his eyes electric were,
computerized his tongue,
Is that more wrong than Berlioz
on LPs harped and sung?

So much electric fills our lives,
some bad, some good, some ill.
But look! there Shaw and Shake-
speare dance on Channel 7's sill:

A gift of hearts and
minds and eyes to see
our dark/light face,
To weigh and
balance halos/
blights that half-
destroy our race;



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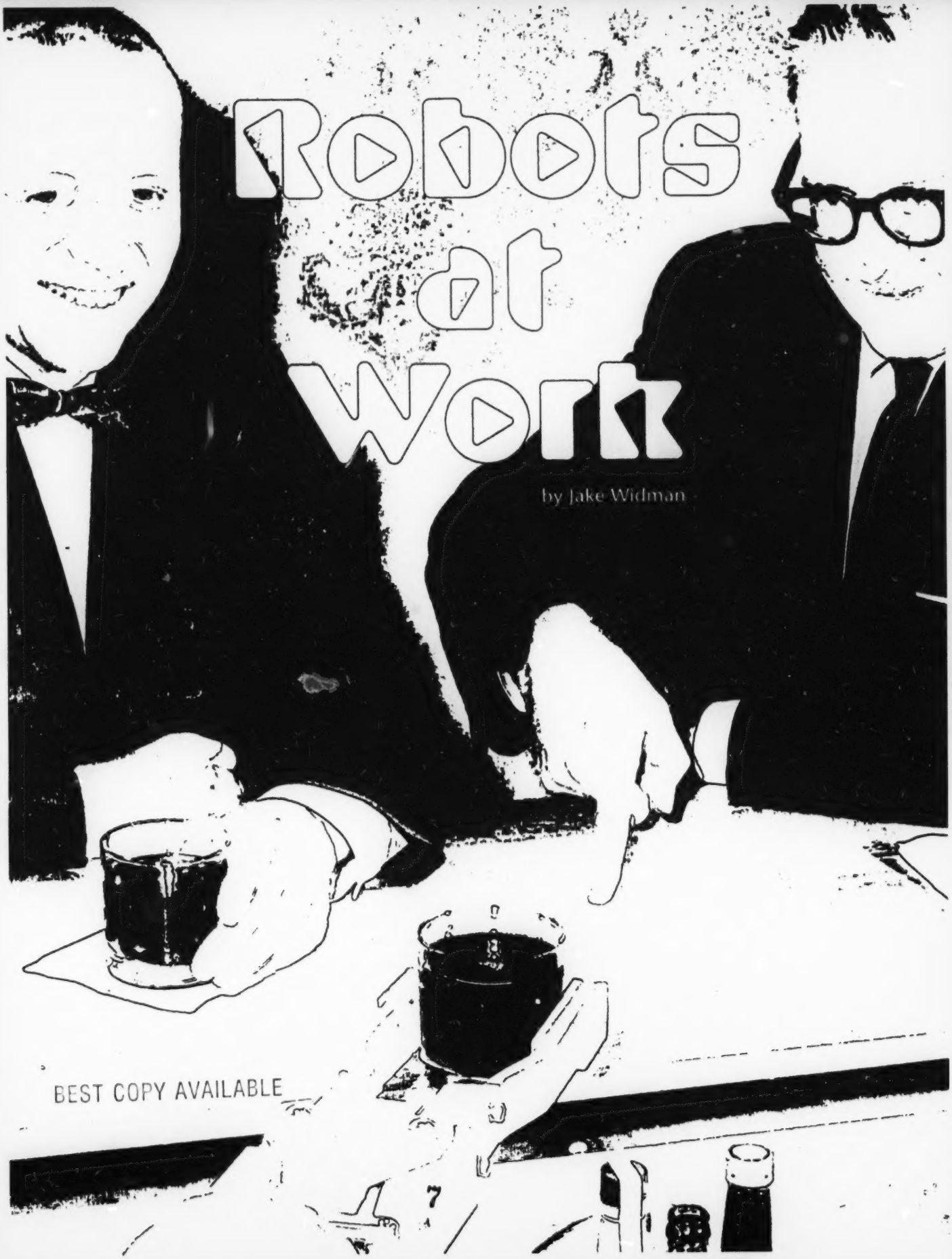
Run Round in Robot Towns

To midget make our rocket-ships, and squeeze grand Kong down small
Then Giants grow from Shavian seed to taunt, provoke us all.

As man himself a mixture is, rambunctious paradox,
So we must teach our mad machines: stand tall, pull up your socks!

Come run with me, wild children/men, half dires and dooms, half clowns.
Pace robot mice, race robot men, win-lose in robot towns. ☺



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Among the emergency workers that responded to the destruction of the World Trade Center towers on September 11, 2001, were several teams of search-and-rescue robots driven to New York by robotics researchers from as far away as Florida and San Diego. Ranging from the size of a shoebox to the size of a small suitcase, the robots crawled through the wreckage to investigate spaces people could not. Their video cameras sent back pictures to help their operators in the desperate search for survivors.

This tragic mission provides a good example of the kind of work robots do best: extending the abilities of humans and working in environments too dangerous for humans to enter. Working robots have come a long way since the first assembly-line operators—robots that could perform tasks such as welding and painting with a moveable arm and grasping hand, but were otherwise fixed in place on a factory floor. But even as robots become smarter and more mobile, the fear of robots replacing human workers has faded as it's become clear what robots are good for—and what they aren't.

Evolution

The history of true working robots began in 1956, when inventor George Devol met engineer Joe Engelberger. Together they formed a company called Unimation. In 1961, their first industrial robot, called the Unimate, went to work at a General Motors plant in New Jersey. It placed car parts just cast from molten metal into a cooling liquid on an assembly line—a repetitive and dangerous job that human workers were happy to abandon. Robots were soon doing a variety of jobs in automotive plants (still the largest employers of industrial robots), and they spread to electronics plants, food-processing plants, and other factories.

With only one arm, and lacking other humanlike body parts, the Unimate's appearance was a far cry from the humanoid robots portrayed in science fiction. It wasn't very smart, either. The Unimate was what's known as a *first-generation* robot: programmable (and reprogrammable), but lacking sensors and the ability to modify its operation beyond its program. While first-generation robots can operate independently, they can only do what they're told—even though it's possible to tell them to do something different at another time. A robot on an automobile assembly line, for instance, might be programmed to weld or paint in the proper place, but only if the object to be welded or painted is in the correct position at the right time. One of the common hidden costs of a first-generation robot is the need to re-engineer an industrial operation to support the robot's function.

Second-generation robots, which appeared in industrial settings during the 1970s, have some kind of rudimentary senses, such as electric eyes or pressure switches, which enable them to receive feedback and alter their actions accordingly. On an assembly line, for instance, an electric eye could tell the robot whether a part was in position or not; if not, the robot could stop and wait for one to arrive.

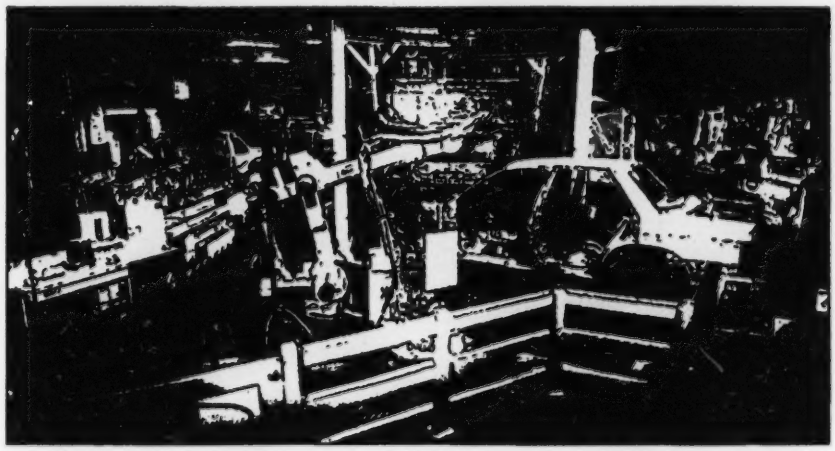
Or say that the robot's job is to fit one part into a hole in another part. If the parts are aligned properly, the two fit together smoothly, and the assembly moves on. But what if the hole is too small, or the parts are misaligned? A pressure switch could tell the robot that the parts aren't fitting together properly, and the robot could put those two parts aside. Even in that case, though, the robot wouldn't be deciding what to do. It would still just be following instructions, substituting one instruction for another based on the working conditions.

The ability to make rudimentary decisions is the hallmark of *third-generation* robots equipped with "artificial intelligence." These robots not only get sensory feedback but also determine their own courses of action based on the information they receive. If that parts-assembly robot, for instance, were a third-generation robot, it might evaluate the situation, decide that the parts were simply out of position, and move them to try again.

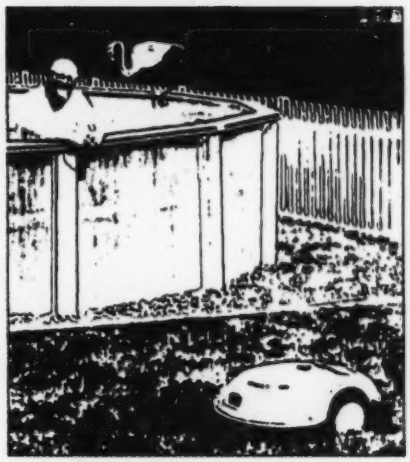
Currently, robots of all three generations are working in industry. The rescue robots at the World Trade Center were *teleoperated*—guided by humans from a distance. (By some definitions, these would not be robots at all.) But researchers envision search-and-rescue robots that would operate completely autonomously, relying on their own artificial intelligence to navigate, and using color and shape recognition to find victims.

Good Jobs for Robots

Our years of experience with working robots have taught us what kinds of jobs they're especially well suited for. First, if there's no variety in the task at all, a dedicated machine (so-called *hard automation*) is usually a better choice than a robot. Consider the standard incandescent light bulb, for instance: General Electric makes millions of them, all the same size and shape, and the size and shape are not likely to change any time soon, so there's not a strong need for a reprogrammable machine along the light-bulb assembly line. But while General Motors may make thousands of a particular kind of car, the shape of the car, and therefore



Facing page: **Engineer Joe Engelberger (*left*) and inventor George Devol (*right*), the designers of the first industrial robot, also appreciate its after-hours uses.** ***Above:*** **Visitors to the Smithsonian can see a robot doing spot welding on an auto body.**



Robots don't only work in factories; some, like the Robomower, can also do chores at home.

On September 7, 2001, a doctor in Manhattan operated on a patient in France by sending high-speed signals to robots in the operating room. It was the first time a surgeon operated on a patient thousands of miles away.

the requirements for a welding machine, change from year to year. For this reason, a welding robot whose instructions can be altered is a better choice.

Compared to humans, robots are perfect for repetitive—but sometimes changing—jobs, which is why they found a place so quickly on assembly lines. Humans get tired and bored, while robots never do. And it's not just fatigue and boredom at issue: Repetitive jobs require a consistency that human labor often cannot supply. Whether it's applying a line of glue of the same height each time, or applying paint at a consistent thickness, robots are better at producing the same result every time than humans are.

Another obvious role for robots is in situations where the conditions are dangerous to humans. The Department of Energy, for instance, has been working on developing the Autonomous Robotic Inspection Experimental System (ARIES) for inspecting drums of low-level radioactive waste. The drums are stacked in warehouses; the ARIES unit is designed to travel up and down the aisles, assessing the condition of the drums and feeding the information into a database.

The U.S. Army is working on a similar system, called the Mobile Detection Assessment Response System (MDARS), to conduct surveillance in warehouses and other structures. Choosing from a library of pretermined path segments, the robot will devise a route through the warehouse and check for intruders, fire, leaks, and other hazards as it goes. The MDARS unit is equipped with sensors that enable it to check its location and avoid obstacles as necessary.

Robots have been used to clean up nuclear fuel spills in power plants, and to gather data on volcanic activity. Other robots are being considered for monitoring the Alaskan oil pipeline and laying and inspecting undersea cables, while NASA continues to develop robots bound for jobs

Multi-Minirobots

by Louisa Dalton

There's Strength In Numbers

Miniature robots, like this MicroRunner submarine, use teamwork to do big jobs.

A half-dozen of what could be soda cans roll into the room. They scatter under the furniture and into the corners. One rolls under a table. One falls down the heating vent. Another gets wedged under the couch. The woman who walks into the room an hour later notices nothing unusual. But her movement has already been detected as these miniature surveillance robots start sending pictures to a room a few doors down.

"You don't expect that something so small has a camera," says Maria Gini, one of the robots' creators at the University of Minnesota. Nor would most expect a small cylinder to move on its own, hop over small obstacles, scan for dark corners, or communicate with a computer a hundred feet (30 m) away.

These Minnesota "scouts" are part of a trend in robotics to build flocks, clusters, swarms, even armies of small, disposable robots. Collectively, they're designed to perform dangerous and tedious tasks: keep surreptitious watch, search a smoke-filled room, or explore the surface of a cold planet. Individually, though, they're no super-robots. Not faster than a speeding bullet, and able to leap over only very short objects, each scout is considerably dumber than most robots you'll meet.

The Japanese company NEC hopes that its PaPeRo personal assistant robot will be more friend than slave. Designed for maximum interactivity, it answers verbal commands, recognizes faces, delivers e-mail messages, and performs a song-and-dance routine.

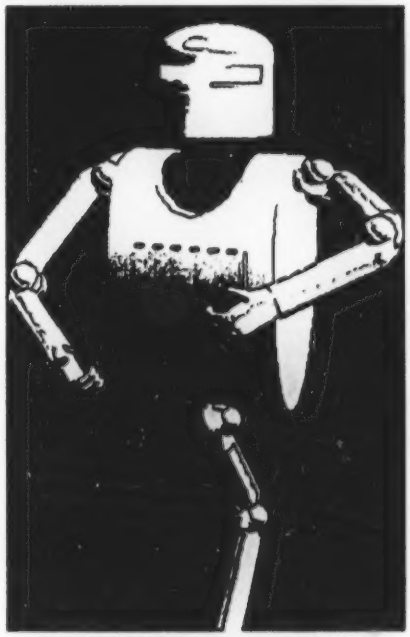
in space. All of these scenarios involve environments that are inimical to humans but no problem for a properly designed robot.

Perhaps surprisingly, though, today's robot industry is quite small, accounting for only a tiny fraction of the gross domestic product of the United States. (The industry is considerably larger in Japan, although still not as huge as might have been expected.) The "robot revolution" predicted for the 1980s—which envisioned robots in every kitchen, cooking our food and washing our dishes—failed to materialize. Robots just hadn't become skillful enough to perform such complex tasks. Disillusionment set in, and many robot manufacturers went out of business. But it now seems that the revolution may simply have been predicted to occur a few decades too soon. In Japan, for instance, a prototype of a personal assistant robot combines currently available robotic features, including voice recognition and visual recognition, with the ability to talk, sing, and dance.

Into the Future

The future of working robots lies in our ability to make them smarter and, often, smaller. Smarter robots will have better sensors, along with more processing power and "intelligence" to make decisions based on what the sensors tell them. Many researchers, for example, are trying to improve robots' vision-based perception by making them better able to interpret what they see—to improve their pattern recognition.

A robot whose task involves manipulating an object, for instance, has to recognize that the object is in front of it. That's no problem if the object shows up in the same orientation every time. But what would be easy for the human brain—recognizing an object even if it's upside down or rotated ninety degrees—is very difficult for a robot, unless every possible orientation is programmed into it. One approach is to program the robot to recognize key attributes of an object's appearance, such as the length and angle of intersection of two curves. If these



NASA's humanlike Robonaut may one day perform the dangerous, time-consuming repairs to spacecraft now done by astronauts during space walks.

In fact, the one that fell down the heating vent is no great loss. With a fleet of mini-robots scouting out an area, losing a few is part of the plan.

The idea behind creating multiple mini-robots is that there's power in numbers. Trying to design one robot to do everything is often inefficient and expensive. If it breaks down or can't finish a task, not much can be done. Creating a small swarm of relatively inexpensive robots to share the workload is sometimes the better option.

It's the same strategy that insects and small crustaceans have been using for millions of years, says Chuck Pell, a minirobot creator at Nekton Research in North Carolina. While mammals spend a great deal of time and energy producing a few healthy, highly capable offspring, brine shrimp and ladybugs blithely send out hundreds and thousands of immature, vulnerable progeny. That many will perish is factored into the overall scheme.

Nekton's robots, called MicroHunters, are miniature submarines. The first sub they developed is about the size of a pinky finger. One moving part drives the robot. A propeller on the hind end spins it in the water in a curious spiraling, forward motion—a clever mimic of the movement of one-celled swimmers such as paramecia and sperm.

In the last few years, six-inch and sixteen-inch versions have been added to the fleet. The six-inch robots hunt for a light source in three dimensions, homing in on the signal and going directly to it. The sixteen-inch subs, equipped with a host of on-board sensors that collect information about such things as depth, sound, and magnetic fields, follow 3-D search patterns and send data back to the researchers. Models that will track chemicals or follow a sound, as well as gather data, are now under development.

Like the soda-can robots, the subs are not extremely bright. But they needn't be. Like ants or bees, their effectiveness is really in the number of entities independently doing the same thing. Just one ant won't make a dent in a piece of bread. But get enough ants and

attributes are present, no matter how they're oriented, the robot can conclude that it's seeing the right thing.

Factory robots tend to be large machines, which suits their purpose as, say, arc welders. But tiny robots are appropriate for a whole range of different kinds of jobs. The sidebar on page 6 discusses the advantages of robots the size of a soda can. But robotics visionaries talk about robots smaller still—*nanobots*—which might be as small as a hundred nanometers. (A nanometer is one billionth of a meter; a thousand nanobots would fit in a cross section of a human hair.) Some researchers, for instance, are working on adapting bacteria to drive tiny robots through the bloodstream. Such medical "minisubs" could be used to clear arteries, deliver drugs directly to the site of a cancer, and perform diagnostic functions. Some believe that working prototypes could be seen within a year or two.

But the real dream involves robots that could operate at the molecular level. If a robot could be built capable of manipulating atoms, it could make copies of itself, which in turn could make copies of themselves, until there were billions of tiny assembler robots awaiting instructions. At that point, visionaries say, we would stand on the brink of a world in which robots cured diseases by repairing individual cells; in which food could be synthesized in virtually limitless amounts right from the raw atoms in the air; in which an old pair of shoes could be broken down and reassembled into . . . pretty much anything. ☺

From outposts like this one, future robotic missions to Mars could manufacture fuel that would be used to send sample materials to Earth for analysis.

they'll carry away the whole picnic.

One job suitable for the MicroHunters is water-quality surveillance. Monitoring is better undertaken by a large force of miniature robots than by a single sophisticated machine. The ocean is deep, and satellites, ships, and buoys gather data mostly from the thin slice on top. Simple, cheap submarines are ideal for taking many readings at once to create a three-dimensional picture of the ocean. In the future, the submarines may also check for leaks in underwater pipes or hulls, look for lost shipping containers, or assist the Coast Guard with search-and-rescue missions. And once they've proved themselves here on earth, the MicroHunters may find themselves traveling far from home. There's evidence that a huge ocean lies under the icy crust of Jupiter's moon Europa, and the MicroHunters might be the perfect tools to search that ocean for signs of life.

Minirobots are not yet being manufactured on a large scale. Most need a bit more work. Their designers struggle with finding enough space for bulky batteries and sensors, and with finding creative ways for the robots to communicate with each other and with us. As technology improves and shrinks, the minirobots will too.

The United States government is funding the development of the submarines, scouts, and other minirobot projects through the Defense Advanced Research Projects Agency (DARPA), which envisions military applications. The scouts are built to a strict volume so, for example, they're small enough to shoot out of a grenade launcher. Yet minirobots could play many civilian roles as well, including scouting airport fences, surrounding a toxic spill, or searching for human life after an earthquake.

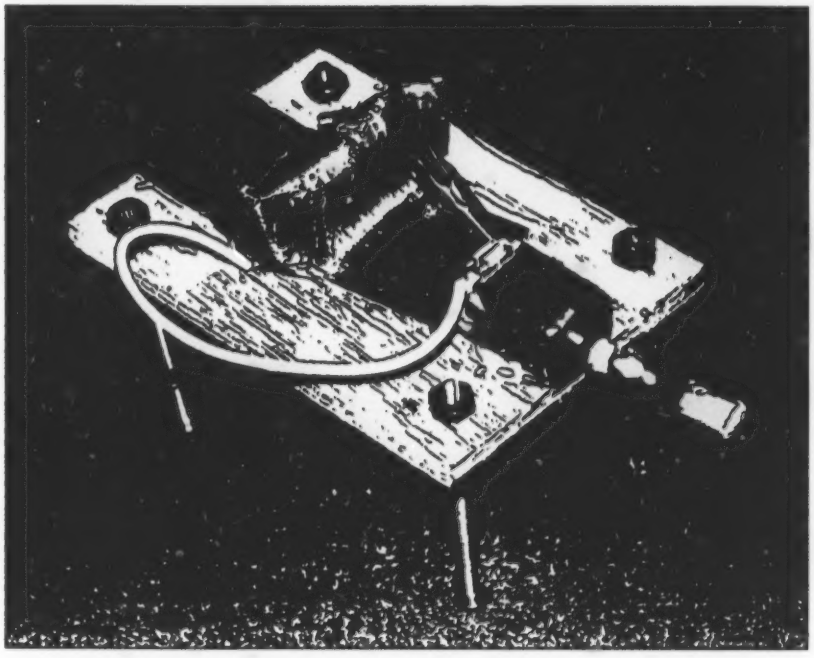
Whatever the task, minirobot designers have taken a lesson from the small animal world. The tiny and the weak (give or take a few hundred) can outlast the big and the strong. ☺

Try This!

by Modesto Tamez

Make a Vibrating Robotic Bug

Have you ever sat in an old car that shakes and rattles, or used an electric massager to sooth your tired muscles? These devices are examples of motors that run unevenly. Knowing this led me to design a simple, inexpensive robotic bug.



Materials

- foam core, plywood, or cardboard, ¼-inch thick
- drill and drill bits, 1/16-inch and ¼-inch
- 4 bolts and 8 matching nuts (I use bolts about 4 inches long and ¼ inch in diameter, but the size can vary)
- hot glue gun and glue
- small 1½-volt motor (available at RadioShack and most hardware stores)
- dowel, ¼ to ½ inch long
- pliers
- a small bolt and nut
- 2 pieces of copper wire, 2 inches long
- masking tape
- AA battery

Assembly

1. Cut the foam core, plywood, or cardboard into a piece about the size of your hand. (The size of the board can vary, depending on what size you want your robot to be.)
2. Drill ¼-inch holes in each corner of the board. Insert the ends of the 4-inch bolts in the holes, with one nut below the board and another above to secure the bolts. These bolts are the robot bug's legs.
3. Using a bead of hot glue, attach the motor to the top of the board, making sure that the motor shaft (the rotating pin that comes out of the front of the motor) is hanging over the edge.
4. Holding the dowel in a pair of pliers, use the drill and 1/16-inch drill bit to drill a hole into the end of the dowel. Place a small bead of glue on the end of the motor shaft, and insert the shaft into the hole.
5. Glue the small nut and bolt onto the side of the dowel. (It doesn't matter exactly where you glue them; they are just to make the motor run unevenly.)
6. Connect the pieces of copper wire to the back of the motor.
7. Tape the battery onto the top of the board.

To Do and Notice

Stand the robot on its legs, and tape the free ends of the wires to the positive (+) and negative (-) ends of the battery. Notice that the dowel begins to twirl and the body starts to shake. When you let go, the robot will start walking.

The beauty of this activity is that by changing different parts of the bug you can change the way it moves. For example, try shortening the legs on one side of the robot. (You can do this by screwing two of the bolts further into the board.) Notice that the robot will now walk in a circle, like a dog chasing its tail.

There are many other ways to modify this simple robot. It has been my experience that the people who do not "stay within the lines" are the people who create the most interesting bugs.

So What?

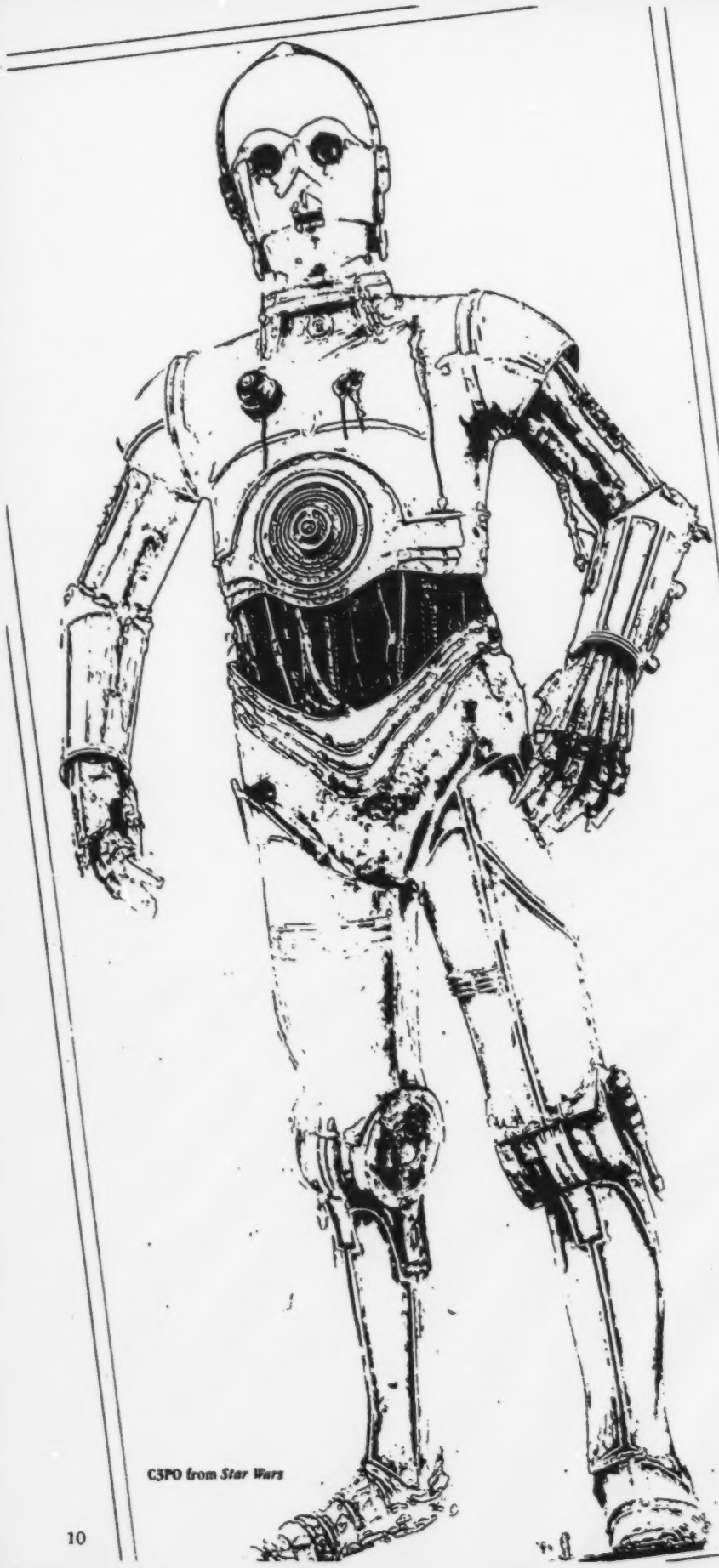
Is this simple toy really a robot?

According to one contemporary definition, a robot must be controlled by a programmable computer, it must have several degrees of freedom, and it must be able to affect its environment. Does the robot bug meet these criteria?

Of course, our robot bug doesn't have any silicon chips inside. However, like a computer, it does have parts that allow it to follow logical instructions. When you change the length of the legs, the device follows this set of directions: If the left legs are shorter, go forward and left; if the right legs are shorter, go forward and right. In that sense, the bug is programmable.

The robot does have several degrees of freedom, because it can move forward, left, and right. And it can affect its environment: It can hit things and can scare or attract cats.

Therefore, the bug is a robot—if only just barely. 😐



C3PO from *Star Wars*

The Robot in the Mirror

What Robots in Film and Television Tell Us About Ourselves

by Hugh McDonald

I've been watching science fiction movies for days and nights on end. This is not a new pastime; I've loved them since I was a kid. Ridiculous aliens, toylike flying saucers, eerie theremin music—I never get tired of it, and the variety of offerings on the SciFi Channel and at the video store suggest that I'm not alone. But lately, I've been paying close attention to the robots: What do they look like? How do they act? And what do they tell us about ourselves?

If its presence in popular culture is any indication, artificial life has fascinated us for far longer than film and television have been in existence. In Homer's *Iliad* (circa 800 B.C.), maidens made of gold assisted the smithy Hephaistos, and the bronze giant Talus patrolled the island of Crete. The legend of the Golem, an animated man of clay, has been a part of Eastern European and Middle Eastern mythology for hundreds of years and is even mentioned in the Talmud.

Karel Čapek first introduced the word *robot* in his play *R.U.R.* in 1921.

A man is something that, for instance, feels happy, plays the fiddle, likes going for walks, and, in fact, wants to do a whole lot of things that are really unnecessary.

—*R.U.R.*

Centuries later, robots and their kin continue to play a key role in fiction, and their presence has been especially powerful in film. Cinematic robots have demonstrated an astonishingly wide range of appearances and personalities; in fact, since the 1920s, robots have played memorable roles in at least eighty films and more than forty television shows.

But why our enduring fascination? Perhaps it's because robots offer perspective on so many aspects of our world and ourselves. Their depictions in film have been driven by technological, social, and political forces, and they have reflected our own evolving views of what it means to be human, and of the nature of life itself.

The word *robot*—from the Czech *robota*, meaning "forced labor" or "slave"—was introduced by Karel Čapek in the play *R.U.R. (Rossum's Universal Robots)*. Published in 1921 (and probably influenced by Paul Wegener's 1920 film *The Golem*), the play followed a race of robots from their creation to the eventual overthrow of their human masters—a theme that has been explored time and again in robot fiction. In fact, many of the themes linked with our modern notions of robots have been around since the beginning of cinema: questions of our responsibility to the beings we create, musings about their emotional lives, even worries about machines replacing humans. The earliest artists to portray robots on film explored all these issues, and they did so when the technology to create robots was just a dream.

Implacable Enemies

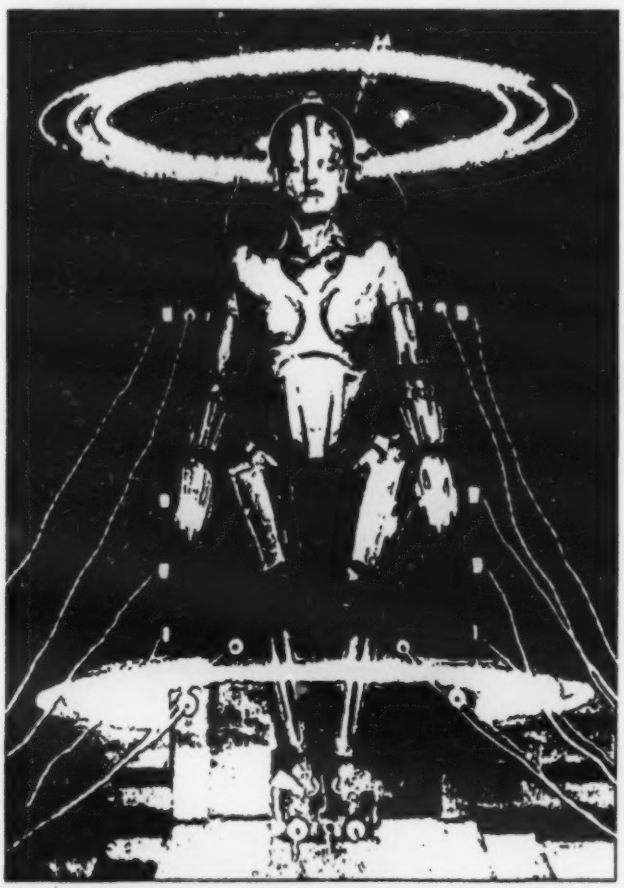
Perhaps the most consistent portrayal of robots in film has been as relentless foe, a cold, intelligent, immensely powerful enemy. One of the earliest and most famous depictions was the temptress Maria in Fritz Lang's classic *Metropolis*. At the time of its release in 1927, much of the world's industry was caught up in rapid mechanization, and this, along with an increasing threat of totalitarianism, aroused fundamental fears in the hearts of millions.

Reflecting these fears, the world of *Metropolis* was an industrial nightmare, its people living only to tend huge machines. Initially, Maria was obviously mechanical (though clearly made in the image of a woman). But Rotwang, her inventor, clothed her in the skin of a real woman and sent her out to destabilize the workers. Rotwang envisioned a world in which artificial creatures like Maria rendered human workers obsolete. But rather than robots freeing humans from drudgery, the unsettling implication was that people themselves would become obsolete. As Rotwang exulted, "I have created a machine in the image of man that never tires or makes a mistake. . . . Now we have no further use for living workers." In the end, however, the robot's true nature was exposed, and she met a just, if barbaric, end.

In the decade after *Metropolis* was released, increasing political tension finally culminated in the Second World War. The "space race" began soon after, based largely on the technology of rocketry developed during the war. The Soviet Union's launch of *Sputnik 1* in 1957 inspired fear in millions of Americans but also galvanized scientists in the United States to tackle the problems of space travel. As we began to voyage through the universe in real life, we actively explored it on film—and imagined the alien entities, living and robotic, that we might meet along the way.

During this golden age of science fiction, robots became an increasingly common and forbidding presence in cinema. Gort, from 1951's *The Day the Earth Stood Still*, was possibly the most forbidding of all: Stark and imposing, he was a massive, unadorned creature of shiny metal who beamed a fearsome death ray from his single eye.

Gort was not made by human hands, but by extraterrestrials on a reconnaissance mission to Earth. Perhaps predictably, given the fearful tenor of



In *Metropolis*, the robot Maria threatened to make human workers obsolete.

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In *The Forbidden Planet*, Robby *(left)* inspired feelings of trust, while Gort *(right)* from *The Day the Earth Stood Still*, evoked fear.

the times, we Earthlings reacted uncharitably and attacked Gort's master, Klaatu, inciting the robot to silently stalk Washington, D.C. (The classic order "Klaatu, barada nicto!" was Gort's command to rescue his master.) Eventually, Klaatu offered the world an ultimatum we were also facing in real life: Learn to control warlike impulses or face extermination.

Although more an instrument of justice than of evil, Gort was an explicit threat to everything in our world—and the robot as threat has played a continuing role in film. Some of these were robots we built and then lost control of, suggesting an underlying fear about our ability to contain the technology we create. The robotic gunfighters (led by Yul Brynner) in the interactive amusement park of 1973's *Westworld* went homicidally haywire, and the silver police robots in 1971's *THX1138* became brutal enforcers of a totalitarian regime. In 1979's *Alien*, the robot Ash metamorphosed from cool scientist to murderous assassin to advance the corporate agenda of his masters.

Other threatening robots came from additional places and times. In 1984, *The Terminator* (the nearly indestructible Arnold Schwarzenegger) came from the future to destroy the ancestor of an enemy, and on television, the Cylons, from the 1970s series *Battlestar Galactica*, were the last artifacts of a dead race trying to eliminate humans from the galaxy. Like Maria, many of these malevolent robots met horrific ends, underscoring the idea that soulless evil will ultimately be destroyed.

Faithful Servants

The history of film robots as faithful servants has been almost as extensive as that of robot villains. Robby, from 1956's *Forbidden Planet*, was the iconic robot servant and guardian of the time. With blinking lights, spinning wheels, and a sonorous, mechanical voice, Robby was dutiful and endlessly resourceful, capable of feats of strength, dexterity, and invention. He even made clothes for his master's daughter and synthesized whiskey for a thirsty space cook.

But perhaps Robby's most important trait was his trustworthiness. Following the influential guidelines for robot behavior first articulated by scientist and writer Isaac Asimov (see page 17), Robby was unable to harm a human being. Although his prodigious strength suggested what he might be capable of, science kept Robby in check.

As the concept of robot as protector and sidekick spread through science fiction, Robby was followed by a long line of faithful, obedient, even friendly robots. C3PO and R2D2 from 1977's *Star Wars*—the primary robots in a film filled with robots of every description—were amazingly skilled and undyingly loyal friends and servants to their human masters. This pattern carried through to television as well. The robot B9 ("Danger! Danger, Will Robinson!") was the very Robby-like servant and protector of the family in the mid-1960s TV series *Lost in Space*. (In fact, both B9 and Robby were designed by the same man, Robert Kinoshita, although B9 was considerably more prone to wry humor than the generally stoic Robby).

Creatures like these were born out of a positive response to the technology of the times. Rather than highlighting our fears about machines gone amok, they reflected our hopes and dreams about the swiftly advancing technology surrounding us.

Blurring the Lines

Robots finally became a fact of real life in the 1960s, when industrial robots began to appear on automobile assembly lines. While these early robots weren't very sophisticated, scientists were beginning to explore artificial intelligence, and it became easier to imagine robots that could truly think—and possibly feel. This set the creators of cinematic and TV robots on a path that explored the idea of robots with a wider range of emotional experiences. Along the way, it became harder and harder to use emotion—or the lack of it—to differentiate robots from ourselves.

One of the most human additions to the emotional repertoire of robots was their ability to have nuanced relationships with humans and with each other. In Woody Allen's *Sleeper* (1973), the citizens of the future interacted easily with hilariously tuxedoed butler robots and combative tailor robots. The protagonist even acquired a mechanical pet, the robot terrier Rags ("Woof woof. Hello, I'm Rags. Woof woof."). In *Star Wars*, R2D2 and C3PO had emotional ties to their human masters, and they also had a strong relationship with each other.

On television, the female robot AF709 appeared in the 1964 series *My Living Doll*. In this short-lived show, the robot (Julie Newmar) lived with a psychiatrist (Bob Cummings) who tried to teach her to be a perfect human female.

Rosie, the Jetson family's maid, helped viewers imagine robots in their own homes.

In *The Day the Earth Stood Still*, the forbidding robot Gort's extraterrestrial master, Klaatu, threatened to destroy the world if humans could not control their warlike impulses.

His efforts to instill ideals of docility and obedience not only confused his beautiful mechanical student, but also hinted at the explosive changes that were soon to rock the relationship between the human genders in the real world.

Robots even made comical inroads into Saturday-morning cartoons. The dilapidated Rosie was the robot maid of the 1960s series *The Jetsons*, often comically falling apart as she heroically met the household's needs. The humor masked an important milestone, however: It was now possible to imagine robotic devices as common household helpers.

As robots became more and more lifelike, in the real world and on the screen, they began taking on more human qualities. Increasingly, they were shown experiencing emotions. *Star Wars*' R2D2 emitted plaintive sighs when frightened and happy chirps when delighted, and the nervous C3PO's voice trembled at the approach of danger. The diminutive Huey, Duey, and Louie in 1971's *Silent Running* were clearly inseparable, and when one was injured, the others, as well as the film's remaining human astronaut (Bruce Dern), were deeply affected.

In a natural evolutionary step, cinematic robots depicted as having emotions could also perceive themselves as being alive—and as living beings, they were troubled about their identities. A classic episode of the ever-popular original *Star Trek* series from the late 1960s followed a spacefaring robotic entity searching the cosmos for its creator, nearly resulting in catastrophe for the *Enterprise*. Two decades later, *Star Trek: The Next Generation*'s android Data battled with the tension between logic and emotion as he further blurred the lines between machine and man.

The increasing emotional complexity of film robots has also drawn the people around them into the quest for meaning and identity. In *Bicentennial Man* (1999), a robot (Robin Williams) is faced with a choice between the durable existence of a machine and the fleeting pleasure of being human—which includes the opportunity to grow old along with his human companion. In 2001's *Artificial Intelligence (A.I.)*, as an artificial boy struggles to become fully human, the humans around him wonder about their own emotional responses to him.

The moral lines between robots and ourselves have also grown fuzzier as the mechanical family has been extended to include creatures both artificial and organic. The replicants of *Blade Runner* (1982), while not technically robots (although created rather than born, they were flesh and blood), focused our thoughts on the philosophical differences between engineered humans and those conceived in the old-fashioned way—and made us think about our responsibilities to the beings we create. It's not surprising that we find such dilemmas in film when we are embroiled in debates about cloning and genetic engineering in our daily lives.

At a time when the manipulation of life itself is more and more under our control, it's becoming harder to define what robots are—or to know how we should treat them. Throughout the history of film, robots and their relations have been illustrating the moral complexities of their dual natures, and of our own. While they reflect the political and technological changes in our world, film and TV robots have also become a blank screen upon which we can project possible images of ourselves. ☺

INSIDE THE MIND

Story and Photos by Ste

NICK DONALDSON

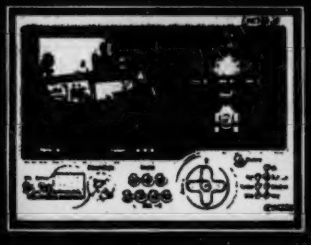
"Ziggy," built around a micro-controller programmed in Java, represents nine months of design and prototyping. "I wanted him to look like an insect," says Nick, "and I wanted to mount all the servos [motors that govern the robot's position] to the body and not the legs. I prefer to keep the legs very lightweight and elegant."

How it works: Ziggy's sonar "eyes" detect objects and send messages back to the robot's central processor. This allows Ziggy to avoid obstacles, making him fully autonomous as he roams around.

CLIFF THOMPSON

The AIBO robotic dog is made by Sony, but Cliff has given it a new intelligence. The dog's sensors respond to commands from a laptop computer.

How it works: A computer sends commands to the robot across a wireless network, enabling the operator to serve as a "virtual jockey." A close-up of the control screen (below) shows live video transmitted from the dog's built-in video cam. The dog can also record audio clips and learn new tricks.



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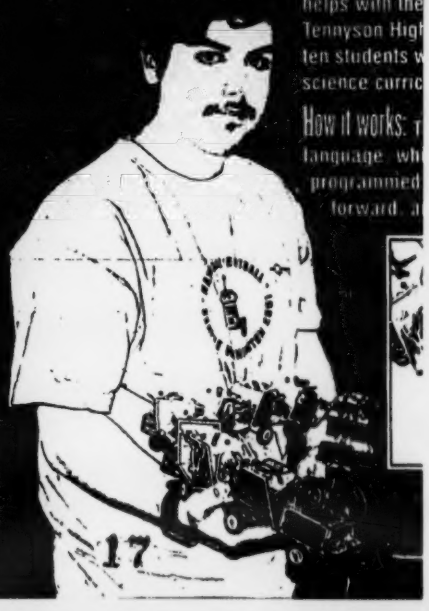
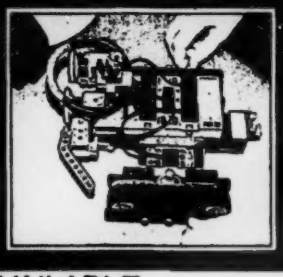


SAM HALVERSON

Sam, age ten, uses a Lego Mindstorm 2.0 computer kit to program his robot. "He knows the program pretty well," says Sam's dad, but for him to really understand the programming and how the sensors function will take more time.

How it works: Sam constructs a program on his PC, then downloads it to the Lego robot through an infrared sensor. The robot is programmed to sense light patterns, spin right or left, or go forward.



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Kearsley

Robot Games

In a standing-room-only crowd at the Exploratorium, spectators cheered in delight as electronic sumo warriors battled to push each other out of a ring. Robotic AIBO dogs competed in races. Hexapod walkers traversed an obstacle course, demonstrating their unique form of artificial intelligence. And robots with names like "Springy" and "Bugsy" performed their mechanical Marx Brothers–like antics in a comedy routine.

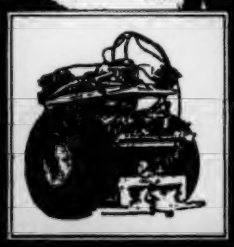
For more than ten years, robot builders have been flocking to the Exploratorium for the San Francisco Robotics Society's annual Robot Games. For the past two years, a robot-building workshop series held at the museum has let Exploratorium Members join in on the fun.

Here's a look at some of the participants in the Robot Games on September 30, 2001, and the innovative designs behind their unique creations.

SUSAN AND RICK WASHBURN

Conan the Barbarian" was built by Susan, a six-year-old Exploratorium Member, for the mini-sumo competition at the Robot Games. Susan became interested in robots after seeing BattleBots on TV. Soon, she was building robots of her own with a Lego Mindstorm 1.5 kit. "She couldn't read the instructions," her dad says. "She just looked at the pictures and, with a little experimentation, began building a wheeled 'car' robot." To control Conan, Rick wrote a BASIC computer program from his daughter's instructions. "If an obstacle is detected by the infrared sensor, turn a little."

How it works: After Susan presses the start button, the robot beeps, counting out a five-second pause. Then it starts forward at full speed into the ring. The robot's "brain" is a microprocessor that controls two sensors. One sensor uses reflected light to avoid the perimeter of the ring; the other, an infrared sensor, is used to detect and battle the opponent.



HERMAN

amily weekends to build. Mark, who has been ter languages since the fourth grade, is the behind the operation. His dad Bill, an engineer onics, Bill is also a parent adviser to the ol Robotics Club in Hayward. His son is one of rticipate in the program as part of the school's

akelike robot is programmed in the C computer trols nine battery-operated motors. Mark croprocessor "brain" to go left, right,

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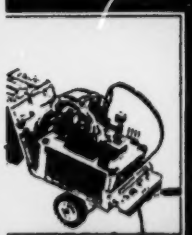
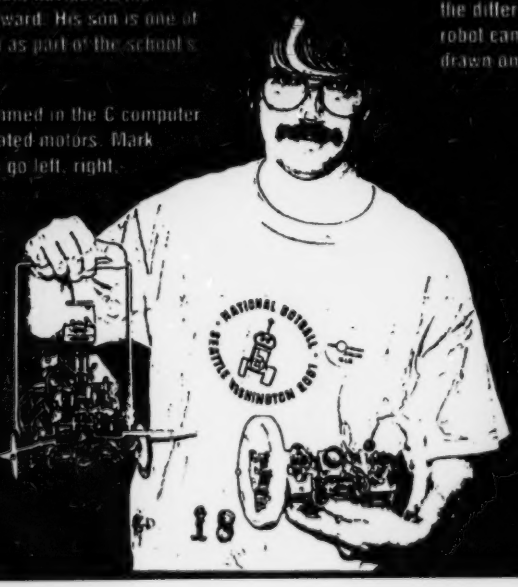
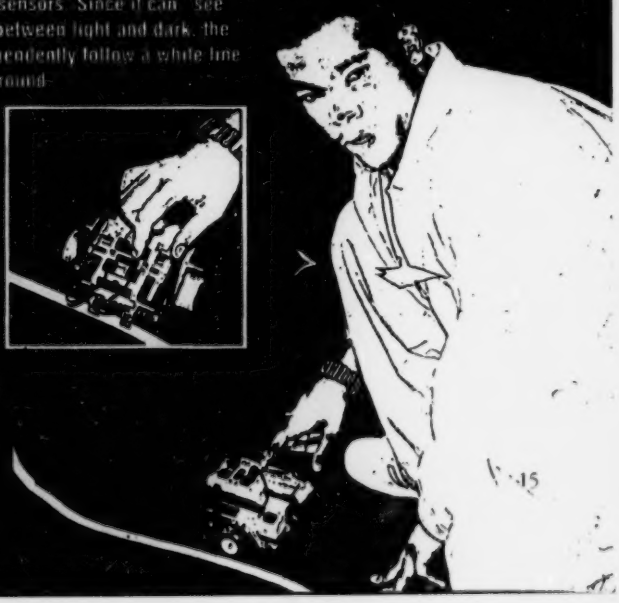


MARCUS ASHLEY

Last summer, Marcus was part of an apprenticeship program in NASA's Robotics Education Project, based at the Ames Research Center in Sunnyvale, California. For two months, he worked with NASA engineers in the robotics computer lab. After the summer program, Mark went back to his DeAnza High School Robotics Club in Richmond to "teach everybody everything I know."

How it works: After programming his Lego Robotlab robot, Mark calibrates the robot's light-sensitive sensors. Since it can "see" the difference between light and dark, the robot can independently follow a white line drawn on the ground.





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Fragments

by Pearl Tesler

You've seen them in construction zones, workers whose only apparent task is to stand and hold a "slow" sign. Tough job, huh? In Tokyo, automatons—only slightly less expressionless than their live counterparts—are muscling in on this employment sector. Lifelike Anzen Taro (Safety Sam) raises and lowers his arm to slow down approaching traffic. Dressed in policeman's garb, Safety Sam is so realistic that oncoming drivers can't tell him from the real thing.

"Can machines think?" In 1950, British mathematician Alan Turing proposed that if machines could exhibit intelligence that was indistinguishable from human intelligence, then the answer would have to be yes. Turing suggested the following experiment, now known as the Turing test:

Two subjects are put in separate rooms. One subject is human; the other, a computer. It's up to a third subject, a human interrogator, to decide which is which. The interrogator can ask any question of the two subjects. The answers are typewritten, so there are no clues from voice or appearance. What's more, the subjects don't have to tell the truth, so the computer can pretend to be human. If the human interrogator can't tell the difference between the person and the machine, then, says Turing, the answer to the question "Can machines think?" is yes.

"The real problem is not whether machines think, but whether men do."
—Burrhus Frederic Skinner, 1969

At around the time he was working on *The Last Supper* (in roughly 1495), Leonardo da Vinci drew plans for the first known robot. The automaton was a knight in full armor; mechanically programmable cable and gear arrangements enabled it to sit up, wave its arms, move its head, and open and close its jaw—all powered by a waterwheel.

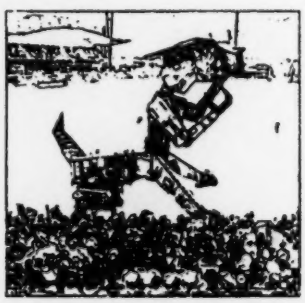
It's not clear whether the robot knight was ever built; if it was, it may have been part of a (then) high-tech amusement park. Like much of da Vinci's work, the final drawings for the robot have been lost. Working from the few existing sketches, The Institute and Museum of the History of Science in Florence has developed a 3-D computer model of Leonardo's robot, shown above.

Try this: Close your eyes and try to touch the tip of your nose with your index finger. Chances are you hit the target, thanks to nerves in your body (called *proprioceptors*) that tell you what position you're in. Some factory robots use a similar method to learn and do their jobs. A human leads the robot through a task, such as spray-painting a car. Position sensors on the robot's joints detect the changing motions and store the data in a microchip. The robot uses this "muscle memory" to repeat the motions exactly, over and over.

"The world of the future will be an ever more demanding struggle against the limitations of our intelligence, not a comfortable hammock in which we can lie down to be waited upon by our robot slaves."

—Norbert Wiener, 1964

What's 40 feet tall, weighs 58,000 pounds, breathes fire, and can bite a Lincoln Town Car in two? Robosaurus, the *car*-nivorous machine that is Detroit's answer to Godzilla. This destructive attraction appears at car and air shows around the country, lifting, squashing, torching, and tossing cars with prehistoric panache.



Controlled by a pilot hidden in the beast's head, Robosaurus is not technically a robot, but a "waldo," a machine operated as if it were an extension of the body. Strapped tightly in his seat, the pilot moves his fingers, arms, shoulders, and feet to control the eighteen different hydraulic movements that animate Robosaurus.

Besides snorting twenty-foot plumes of fire (thanks to propane hot-air-balloon burners) and burping loudly after making a meal of a Mercedes, Robosaurus's guaranteed crowd-pleaser antic is this: He lifts a car high overhead, uses his rotating wrist to point it straight down, then lets it drop fifty feet onto its front bumper.

Yes, there's something duller than school: getting stuck in the hospital with a long-term illness. Scientists at the University of Toronto have invented a telepresence robot called Pebbles that lets hospitalized children attend their classes virtually.

Using a joystick-style controller, a student can speak, see, and hear through an egg-shaped robot that sits at a desk in the classroom. The robot can even raise a robotic hand to answer questions—what it can't do is slump down in its seat to avoid being called on.

"The fact is, that civilization requires slaves. The Greeks were quite right there. Unless there are slaves to do the ugly, horrible, uninteresting work, culture and contemplation become almost impossible. Human slavery is wrong, insecure, and demoralizing. On mechanical slavery, on the slavery of the machine, the future of the world depends."

—Oscar Wilde, 1895

Approximately 90 percent of working robots are employed in factories, and the majority is at work making automobiles. At the General Motors plant in East Pontiac, Michigan, for instance, robots assemble and weld together seventy-three truck bodies per hour. ☺

ROBOTICS has become a sufficiently well-developed technology to warrant articles and books on its history, and I have watched this in amazement and in some disbelief, because I invented it.

No, not the technology; the word.

In October 1941, I wrote a robot story entitled "Runaround," first published in the March 1942 issue of *Astounding Science Fiction*, in which I recited, for the first time, my "Three Laws of Robotics." Here they are:

1. A robot must not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human beings except where those orders would conflict with the First Law.
3. A robot must protect its own existence, except where such protection would conflict with the First or Second Law.

These laws have been quoted many times by me in stories and essays, but what is much more surprising is that they have been quoted innumerable times by others (in all seriousness) as something that will surely be incorporated in robots when they become complex enough to require it.

As a result, in almost any history of the development of robotics, there is some mention of me and of the Three Laws.

It is a queer feeling to know that I have made myself into a footnote in the history of science and technology for having invented the foundation of a science that didn't exist at the time.

—Isaac Asimov, "The Word I Invented," 1980

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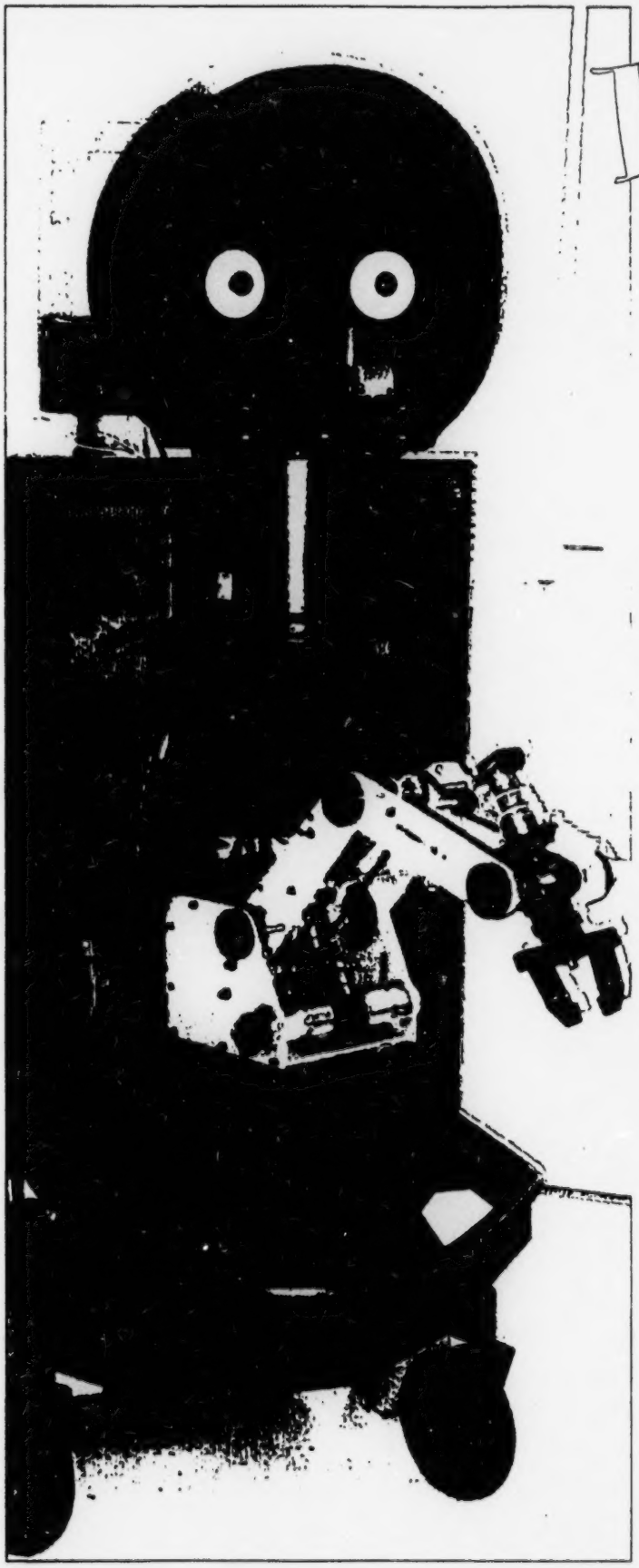


Bringing Up Baby

by Erica Klarreich

"Please don't use that kind of language in front of the robot!"

Setting a good example for an impressionable child is hardly a new idea. After all, human society depends on the careful rearing of infants into responsible, thoughtful adults. But when a youngster is a hulking five-foot-nine assemblage of wheels, gears, and video cameras, giving it a good upbringing may not seem like a high priority.

That is, unless you're computer scientist John Weng. Weng is working to build robots that are as quick to pick up our bad habits as our good ones. And somewhere down the road, he says, they may even achieve the Holy Grail of artificial intelligence: self-awareness.

Experience Is the Teacher

With colleagues at Michigan State University, Weng has built a rudimentary robot named SAIL (Self-organizing Autonomous Incremental Learner) that learns through its experiences with the world, just as a child does. Looking like a cross between a person and an upright vacuum cleaner, SAIL has already learned several of an infant's first activities, such as paying attention to a toy and reaching out to it. It has acquired a vocabulary of about twenty words and has learned to follow simple spoken commands.

From these humble beginnings, Weng hopes to spawn robot progeny that could someday be smarter than he is. "In traditional artificial intelligence, a machine will do reasonable things because the designer is smart, not because the machine is," Weng says. "But a child can learn a language its parents don't understand. That's the power of animal learning."

Robots are taking their time going from the realm of fantasy to the reality of daily life. The reason, Weng says, lies in the way scientists have been trying to design robots. In traditional artificial intelligence, like the kind that went into the chess whiz Deep Blue, a computer scientist writes a program specifically geared towards the task to be executed—a method that works well for something like chess, which has clean rules.

But if you want a robot to perform complicated real-world tasks, Weng argues, the key—paradoxically enough—is not to program the tasks into the robot. Instead, start the robot off with a mind that can structure itself in response to its environment, and then let the robot develop by interacting with the world autonomously, in real time. While many computer scientists have written programs that can learn from experience to perform a particular task, for Weng, it's essential that SAIL should be able to learn tasks that he himself hasn't imagined.

SAIL, which stands for Self-organizing Autonomous Incremental Learner, is Michigan State University's version of a robot "child." SAIL interacts independently with its surroundings and learns from its mistakes—and successes. Actions such as navigating the hallways of the university's engineering building (*above*) and reaching out to grab a toy (*right*) are the result of SAIL's learning by trial and error rather than by preprogrammed instructions.

Weng has endowed SAIL with a developmental program that allows a "robot-sitter" to teach it in much the same way a parent teaches a child. To teach SAIL to reach out to a moving object, for example, the researchers started by moving SAIL's arm to grab the object, the way a parent guides a child's hand when teaching the child to write. After many repetitions, SAIL practiced on its own, receiving encouragement or discouragement from trainers via "good" and "bad" buttons on its back.

Eventually Weng plans to use language to let the robot know how it's doing. "Good job" may be the first lesson. In any case, positive or negative feedback from the trainers becomes part of the information that the robot stores about each experience and considers when it's deciding on a new action. Over time, this will enable the robot to develop long-term values. Humans build up complex values out of such simple beginnings, Weng says.

For now, though, Weng is content with more modest aspirations. Recently, his team has been training SAIL to navigate the intricate corridors of the university's engineering building. "It'll take ten or twenty tries to learn the first corner you show it," says Jason Massey, one of Weng's graduate students. "But the next one takes only half as many tries."

Two video monitors on SAIL's back show its teacher what the robot is seeing at every moment. But the teacher can't see into SAIL's brain—which, Weng says, is the point. Once SAIL's developmental program was put into place, Weng locked off its brain from programmers who might feel the itch to tamper with it to make SAIL perform a particular task.

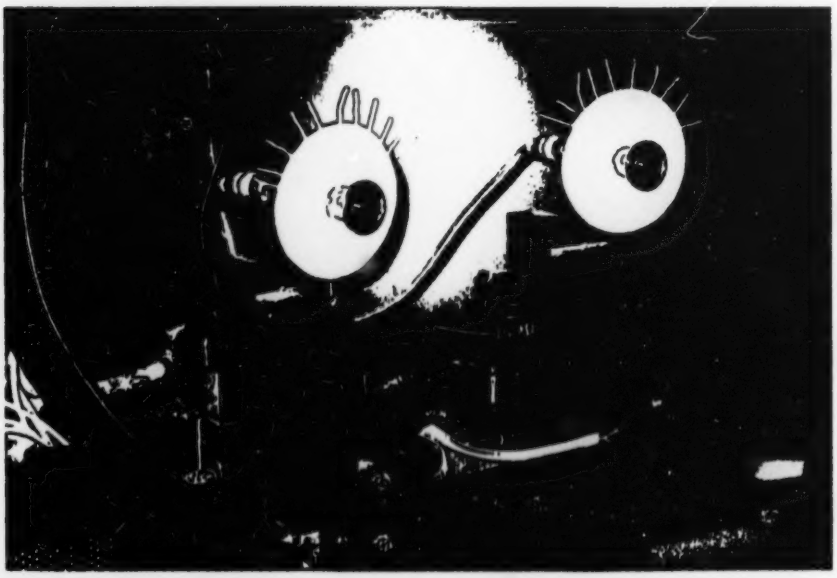
Weng is "taking a huge step towards something much more brainlike than what is normally being done," says James McClelland, a psychologist and computer scientist at Carnegie Mellon University. "What John is fundamentally trying to do is say, 'Look, the human brain doesn't have a programmer. It programs itself in the course of experience. What we need to do is find ways of creating machines that program themselves.'"

A growing body of evidence supports the idea that our own brains are molded by our surroundings. "Although there is certainly some predisposition in the brain," McClelland says, "experience does a lot more in shaping what we come out with than people have argued in the past."

Making Memories

Weng has engineered SAIL to base its actions on the experiences it has already laid down in its memory. To teach SAIL a command like "turn left," for instance, researchers repeatedly turn the robot while saying the words. On each go, SAIL stores a wealth of information, including what it sees as it turns, the sound of the trainer's voice saying "turn left," and the direction and speed of its wheels. If the trainer gives SAIL a command and doesn't impose an action, SAIL sifts through its memory to find the past experiences closest to the current one, and uses those to determine its current action. So if SAIL is instructed to turn left, it will see that previous successful responses all involved turning its wheels in a particular way and act accordingly.

SAIL can't store every experience it has, of course. Imagine if our brains tried to recall every detail of everything that happened to us—we'd soon be overwhelmed. "Each image SAIL takes in has a quarter of a million pixels," Weng says. "It can't record everything, only what's essential." To allow SAIL to respond in real time, Weng wrote a clumping mechanism into the developmental program. When SAIL has similar experiences, instead of storing each one separately, it gathers them into what Weng calls a prototype memory, in the same way a young child might look at many flat surfaces with four legs and finally decide they are all specimens of something called



a "table." Thus, for example, SAIL eventually gathers together the memories associated with the words "turn left" into a prototype, which it refers to and updates as needed. By grouping and regrouping its memories, SAIL constantly restructures its brain in response to the environment.

Learning to Forget

Weng has bestowed another human trait on SAIL that is perhaps undervalued by its possessors: forgetfulness. If one of SAIL's memories fails to be reinforced by succeeding memories, it fades gradually, according to a precise rule. When the memory gets faint enough, it's erased.

Sorting through its brain for faded memories or experiences to merge can take SAIL anywhere from minutes to hours, so when there's a large backlog of memories to be organized, the researchers switch the robot into a sleep mode in which it temporarily stops interacting with the world. So far, the trainers are putting SAIL to sleep manually, but eventually Weng plans to teach SAIL to obey the robot equivalent of "Okay, kids, time for bed."

With time out for sleep, SAIL can keep pace with its environment when it's awake, reacting to changes in real time. And since it's not distracted by activities such as nursing, crying, and diaper changing, it learns some tasks faster than a human baby. Teaching SAIL to reach out and grab a toy, for instance, took the researchers about half an hour. They are now working on building SAIL's vocabulary, trying to teach it more complicated tasks such as recognizing faces, and thinking about ways to improve the developmental program.

The Right Approach?

Of course, the list of things SAIL can't do is much longer than the list of things it can do. And some researchers don't believe that SAIL—or any other robot without preprogrammed cognitive abilities—will be able to develop the traits we think of as strictly human.

Researchers who try to leap past understanding specific tasks run the risk of oversimplifying, warns Patrick Winston, a professor in the artificial intelligence lab at the Massachusetts Institute of Technology. "It's hard to make a program learn if you don't know what, in general terms, it is to learn, and romantic to suppose that you can," he says. "I'm sure we will learn something from their approach, but I do not think it is the answer, in the sense that all else should be abandoned."

Arthur Markman, a psychologist at the University of Texas, agrees that we shouldn't discard traditional approaches lock, stock, and barrel. "But I do think this is an important approach, and it's a good group of people doing it," he says. "We won't know what the limitations are of a particular approach until people actually go out and build the robots, and show what you can or can't do."

But MIT computer scientist Marvin Minsky argues that it's improbable that a purely self-organizing machine will ever be able to generate the complex representations that go into higher-order thought. He points out that cats and mice have much more powerful brains than the SAIL robot, but still they seem to be blocked from learning language. "No matter how much experience they have, there seem to be things these animals simply can't represent," he says.

No one can dispute that, agrees cognitive scientist Mriganka Sur, also at MIT, but no one knows whether a cat or mouse is held back by the structure of its brain or simply by its size. "We have to ask, what is in human brains that is not in cat brains," he says. "One of the amazing things is that we have no clue what the answer is. It would be prematurely limiting ourselves to put arbitrary limits on what robot brains can do."

Weng doesn't expect SAIL to learn complex language any time soon, but the limitations are in the hardware, not the principle, he says. Like human beings, a robot is only as good as the materials it's made of. As more people start building developmental robots, Weng predicts, we'll see dramatic improvements in the quality of the robots' eyes and ears, their body design, and perhaps most crucially, in their processors.

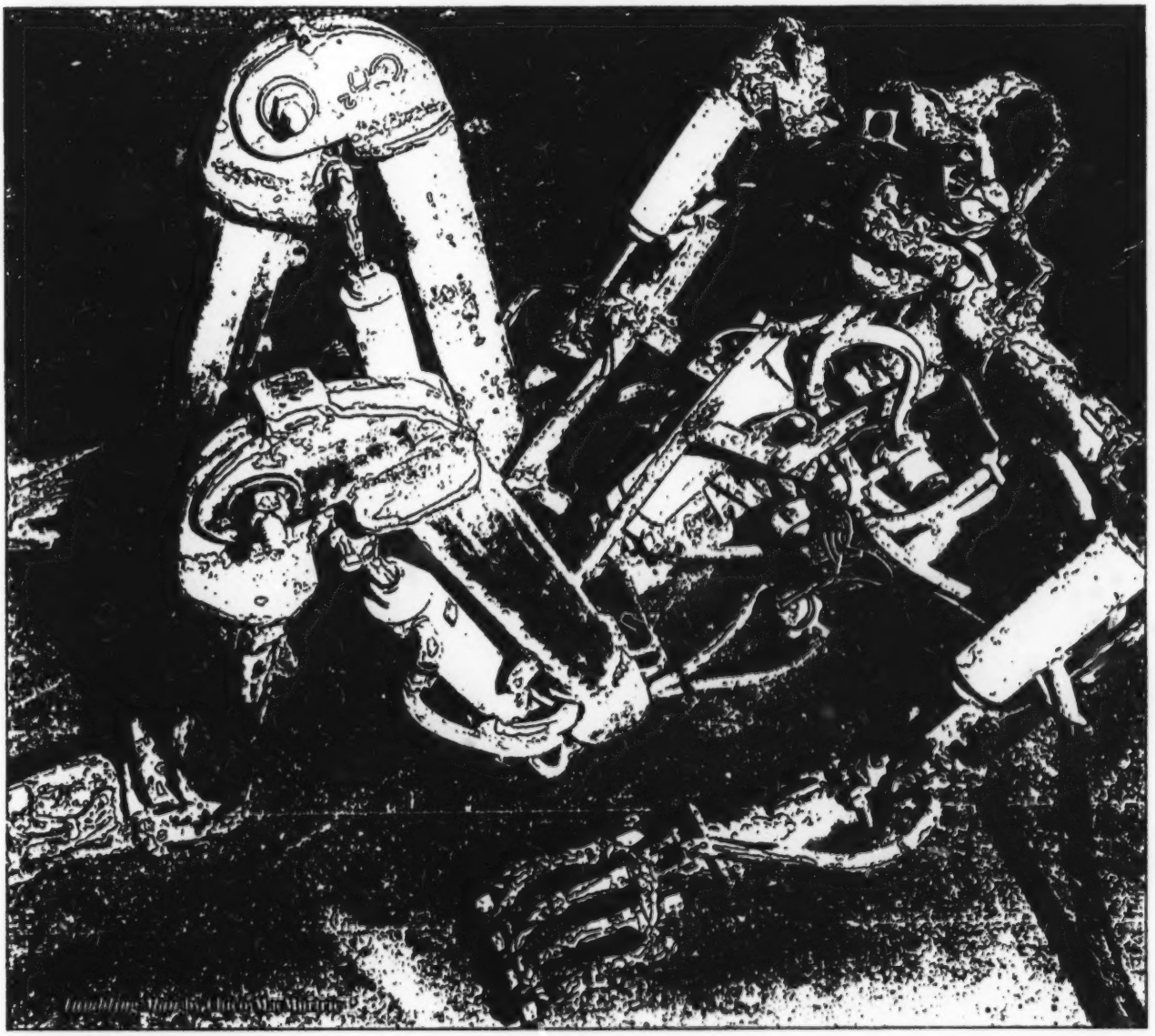
If intelligent robots can someday be built, Weng says, one of their great advantages will be their immortality. Weng likes to tell his students that when Albert Einstein died, his brain was wasted because we couldn't download it into another body. "Biological intelligence is very much tied to the body," Weng says. "But when a robot's hardware gets worn, you can download its developed brain, then upload it into another body."

Developmental robots like SAIL will probably first appear in the toy and entertainment industry, Weng says, maybe within just a few years. Already, a major toy company has been sniffing around his laboratory, looking for ideas for "smart toys." Beyond that, Weng sees developmental robots working in complex, ever-changing human environments. Tasks might include guarding major bridges against potential attacks, or carrying out wartime reconnaissance missions. Unlike robots that have been programmed to learn or perform specific tasks, developmental robots will be able to handle the unpredictability of situations. By sending these robots where danger or extreme environments bar humans, "we can extend our physical limit," he says. "That's a very exciting thing." ☺

ARS ROBOTICA

by Liisa Pine

ROBOTS AS ART OBJECTS, ART TOOLS, AND CREATORS OF ART

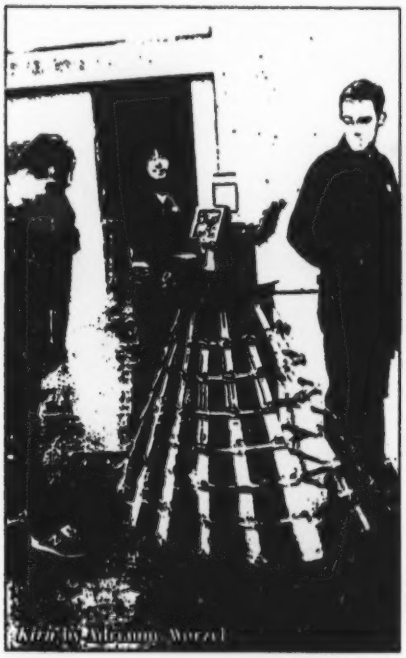


What is it about robots? Clearly, they inspire us far beyond their roles in science and industry. There are robots being built for art installations and film shoots, robots retired from their regular jobs to work in theater and performance, and a seemingly endless supply of them making appearances in sculpture, literature, graphic design, and nearly every other medium. It's difficult to think of another area of scientific research that is as wholly integrated into our imagination and sense of expression.

Around the world, advances in engineering techniques and machinery are expanding the participation of robots in our cultural lives. Artists don't just use traditional art materials to represent robots—they're also using robots to create art.

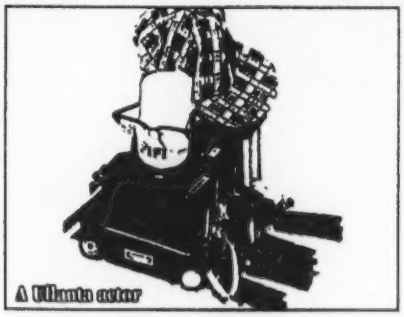
Recently, for instance, if you visited New York's Whitney Museum in person or went to its Web site, you might have met a robot named *Kiru*. Created by artist Adrianne Wortzel, this "cultural curmudgeon" interacted with visitors while exploring the lobby and one of the galleries. Visitors to the Web site randomly controlled his camera "eyes," movements, and speech. By using a video feed and watching colored tiles on the ceiling, *Kiru* was able to keep remote operators from taking him too far afield. But occasionally he got lost all by himself, venturing into one of the elevators and mumbling away, making the ride an unexpected theater experience for museum goers.

Fortunately, robot theater doesn't happen only when machines go unexpectedly off course. One of the production companies that provide drama on demand is Ullanta Performance Robotics, which stages plays with commercially available hobby



Kirin by Takayuki Yuzui

Ulanta Performance Robotics



A Ulanta actor

Rock Thrower
by Chico MacMurtrie

and research robots. With scripts that explore issues such as autonomy, love, and paranoia, the electronic thespians enact a world full of emotion and drama that we might not expect from them.

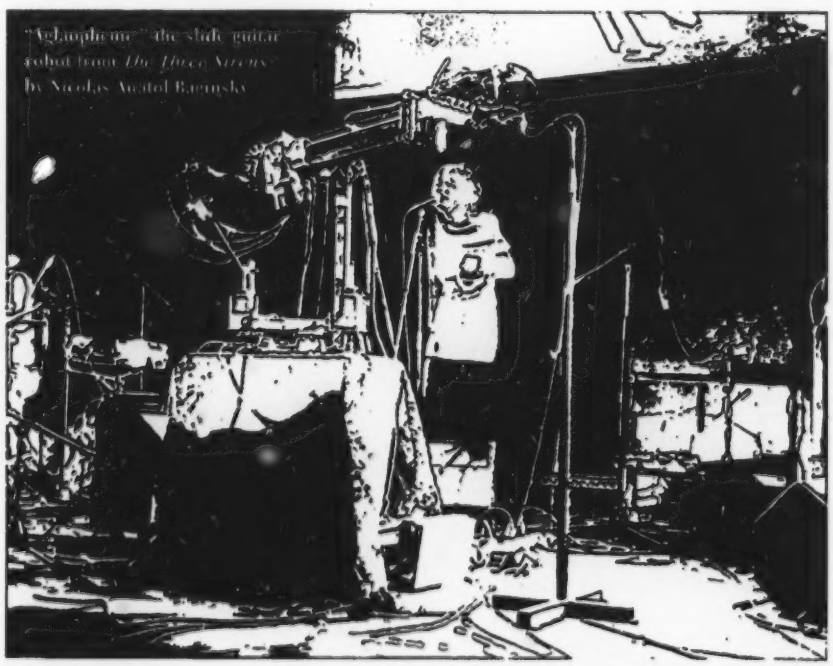
But perhaps the most exciting aspect of robot art today is the art that robots themselves generate. Increasingly complex computing systems and artificial intelligence have provided some of them with what is arguably creativity.

Vanderbilt University hosts a robot called *ISAC* that plays the theremin, an electronic musical instrument controlled by gesture. It's a difficult instrument to play, as there are no exact finger positions; in fact, the musician never actually touches it. Only a small number of people have mastered the theremin, which makes the musicianship of *ISAC* all the more impressive. The heart of what works for *ISAC* is feedback-loop software that gives it "perfect pitch," enabling it to move its arms in response to what it hears.

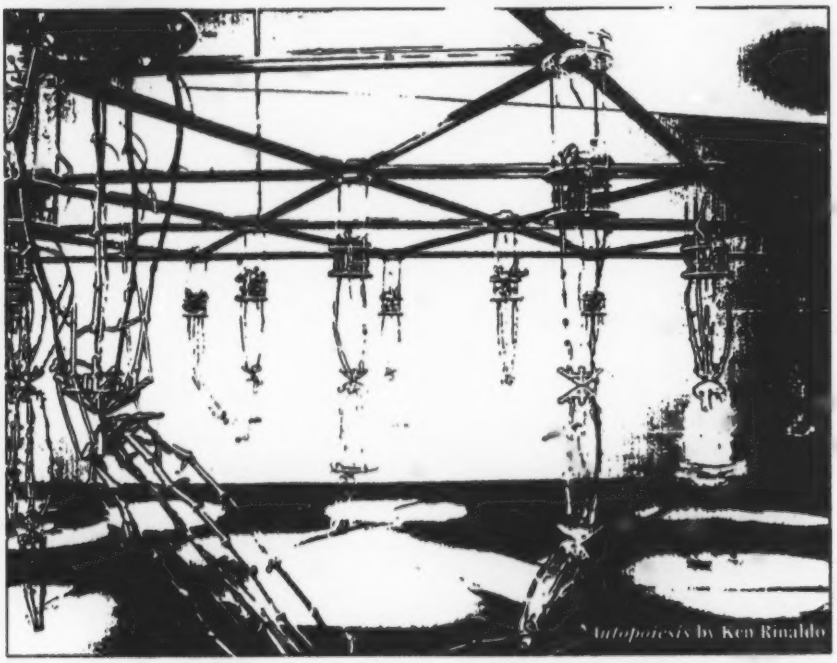
Some robots are both player and instrument. Nicolas Anatol Baginsky created *The Three Sirens*—drum, bass, and slide guitar—that teach themselves how to play. Using neural networks, a strategy that allows the robots to learn from experience, they create their own melodies and improvise with each other.

The Exploratorium has sponsored a variety of robot-related projects. Among the most notable is the Amorphic Robot Works of Chico MacMurtrie, which perform enchanting mechanical and musical scenarios. Along with exhibit developer Dave Fleming and other staff, MacMurtrie created several performances on site and helped turn the Exploratorium machine shop into an extensive robot fabrication house. Out of this collaboration

Vanderbilt University's *ISAC*



"Xylophonic," the slide guitar robot from *The Three Sirens* by Nicolas Anatol Baginsky



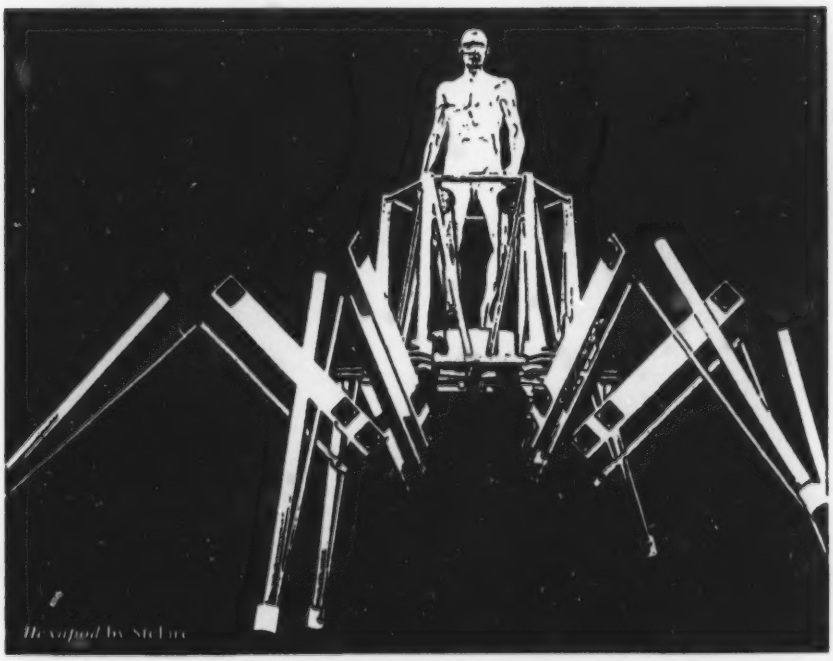
Autopoiesis by Ken Rinaldo

came the man-machine interface that eventually controlled the acrobatic *Tumbling Man*.

The robots in Ken Rinaldo's work are mobile in a different way—enlivened by the approach of human visitors. The multitentacled bots of *Autopoiesis* hang from the ceiling in a gallery. People moving among them activate infrared motion sensors, and the robots move according to the action in the room, and, through a computer network, in response to each other. They also communicate among themselves via an auditory tonal system, and "watch" the gallery visitors with cameras mounted on the ends of their tentacles.

A more visceral example of robot-human interaction is evidenced in the work of Stelarc. Using his own body along with the body of a robot, he reconfigures the processes we usually think of as free will and creativity. In collaboration with The Performance Arts Digital Research Unit at the Nottingham Trent University in Britain, Stelarc became part of a six-legged walking robot. The control system was attached to his body and responded exclusively to his movements—which, in turn, were affected by the movements of the robot.

The art done with and by robots often blurs boundaries between humans and machines and leaves us wondering about the nature of creativity and the ability to make art. Despite all we know about the brain, we can't explain the source of human creativity. Now we must also consider the idea that creativity is not necessarily the exclusive possession of living beings. By mixing robots with art, we gain new perspectives that may help us understand art, science, and, ultimately, ourselves. ☺



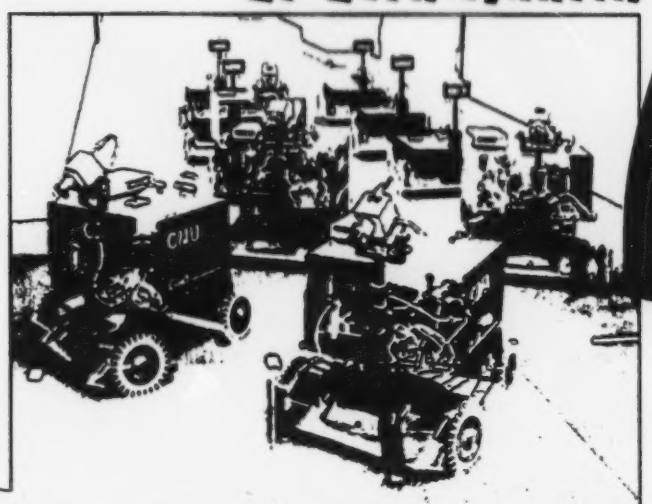
Hexapod by Stelarc

Exoskeleton by Stelarc

RACE FOR T

SOCCERBOTS USE TEAMWORK TO CAPTURE THE PRIZE

BY BETH MARTIN



With a sudden whir of motors, the boxy robots spin and dart across a makeshift soccer field. A robot named Jupp spies the ball and makes his move. He pushes the ball down the field and shoots it into the goal. With no human intervention, Jupp just did what many of us never accomplished in PE class: He scored the winning goal for his team.

In August 2001, this robot and hundreds more on teams from twenty-three countries gathered in the Washington State Convention and Trade Center in Seattle to compete in the fifth annual RoboCup, the world's top robot soccer games. If RoboCup meets its ultimate goal, a team of fully autonomous humanoid robots will beat the human world soccer champions by the year 2050.

The soccer competitions offer intriguing entertainment—and a lot more. Billed as a "sporting and scientific event," RoboCup gives universities that created the players a chance to test their work in many areas of robotics, including machine vision and autonomous navigation. The soccer-playing bots are paving the way for robots that could do all manner of jobs, but, in particular, those that require teamwork. Eventually, robots like these could perform dangerous tasks such as fire fighting, which requires complicated, fast-paced communication and cooperation. Robotic soccer, where team members continually rely on each other to rapidly provide strategic information, offers a perfect testing ground for robots who may someday be programmed to save lives.

RoboCup participants include six-inch-diameter (15-cm) bots that compete on a field the size of a Ping-Pong table to players the size of humans. The robot Jupp described above belongs to the Middle-Size league, which fields teams of four players that are approximately twenty inches (50 cm) in diameter and about 31 inches (80 cm) tall.

These Middle-Size players sport digital cameras for eyes, wheels and bumpers instead of feet, and computer chips and sophisticated software programs that serve as brains. The coaches arrange the players on the twenty-foot by thirty-foot (6-m by 9-m) field, but when play starts, the robots get no help from the coaches. They use their own "eyes" and "minds" to get the ball into the opponent's goal. A closer look at Jupp's game, which pits the Carnegie Mellon University (CMU) Hammerheads against CS Freiburg, the team from Albert-Ludwigs-Universität in Freiburg, Germany, gives us a glimpse into how autonomous soccer robots pull off what had previously been a uniquely human activity.

HE ROBOCUP

The Game's Afoot

By the end of the first half, the score is tied at 3-3. CS Freiburg rallies in the second half to hold off several advances from the CMU Hammerheads. Just minutes before the game ends, Jupp, who plays for CS Freiburg, looks around the field. Like a human player, Jupp must figure out his location in relation to the field, the other players, the ball, and the goal. Jupp "sees" with a palm-sized camera that collects images of the field through a wide-angle lens and sends them to his brain, a laptop computer. The computer's sophisticated software analyzes the images.

Brett Browning, a robotics researcher at Carnegie Mellon, says that the robot's software has to be able to deal with camera images that may sometimes be distorted. Despite distortions, Jupp has to be able to recognize certain objects, from the ball to his opponents. One approach is not to rely on shape alone. "People are very good at that, but software isn't," says Browning, "so we make careful use of color to help make the perception problem easier." Like the other players, Jupp sees the walls as bright white rectangles. He knows his fellow CS Freiburg players by their yellow tags and CMU players by their blue tags. The field is green and the ball is orange.

But the players need to do more than identify the objects around them. They also need to know where those objects are and figure out their own location in relation to all those objects. In addition to his image-collecting camera, Jupp uses a laser-scanner to help locate himself and recognize obstacles. The laser sends out short infrared light pulses that are reflected back by solid objects. The time it takes for the light pulse to return gives Jupp enough information to create a rough map of his surroundings.

The Importance of Teamwork

The combination of camera and laser-scanner gives Jupp good information, but he can perceive only a segment of the playing field. A more global view requires teamwork. While human players communicate with speech and body signals, the robots use a wireless network to share knowledge with each other. Together, using the network as a sort of collective brain, they construct a complete picture of the field. Sometimes a robot misinterprets what he sees, but information from his teammates can correct false impressions.

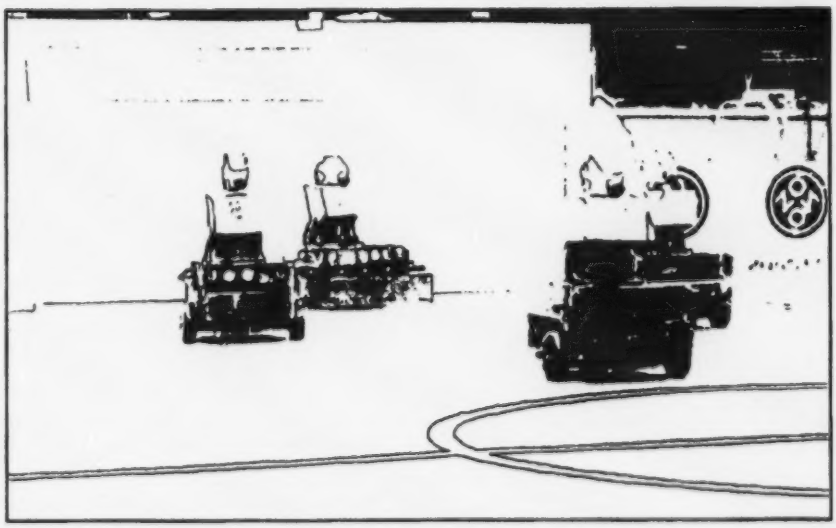
Working as a team, the robots can also develop strategies. Jupp sees the CMU players and a blue rectangle at the end of the field, the CMU goal. Teammate Franz spies the orange soccer ball. A third CS player, Berti, also sees the ball, and can tell that Jupp is in the best position to snatch it. As they share information, the robots agree that Jupp is closest to the ball, and that Berti is in the best position to help Jupp move the ball to the goal. Franz stays back to defend their end of the field along with Sepp, the goalie.

Jupp launches into action by spinning his two motor-driven wheels. Each wheel has its own motor, and can move in any direction. Jupp speeds towards the ball, outrunning a CMU player, and secures the ball with his scoop-shaped bumper. Berti, meanwhile, blocks a second CMU player farther down the field. Jupp pushes the ball along with his bumper, zigzags down the field, and avoids the last CMU blocker before facing the goalie.

The players are still communicating, so they know that Jupp sees an opening to the left of the goalkeeper. Jupp turns slightly, then gives the ball a kick with his springlike kicking device. The CMU goalkeeper tries to intercept the ball, but he's too late. CS Frieburg earns the winning goal.

The crowd cheers as the coaches shake hands and collect the players. Congratulations are offered to CS Frieburg, which advances to the Middle-Size Robot League finals to play the Osaka University Trackies.

Despite fierce competition on the soccer field, a spirit of cooperation prevails, because the university teams freely share their information with the aim of advancing key research areas in robotics and artificial intelligence. Communication, navigation, vision-based perception, and mechanical design improve each year, encouraged by the fun of RoboCup—Improvements that will help working robots of the future do their jobs. Until then, keep an eye out for soccer's rising stars. ☺



Ask Us

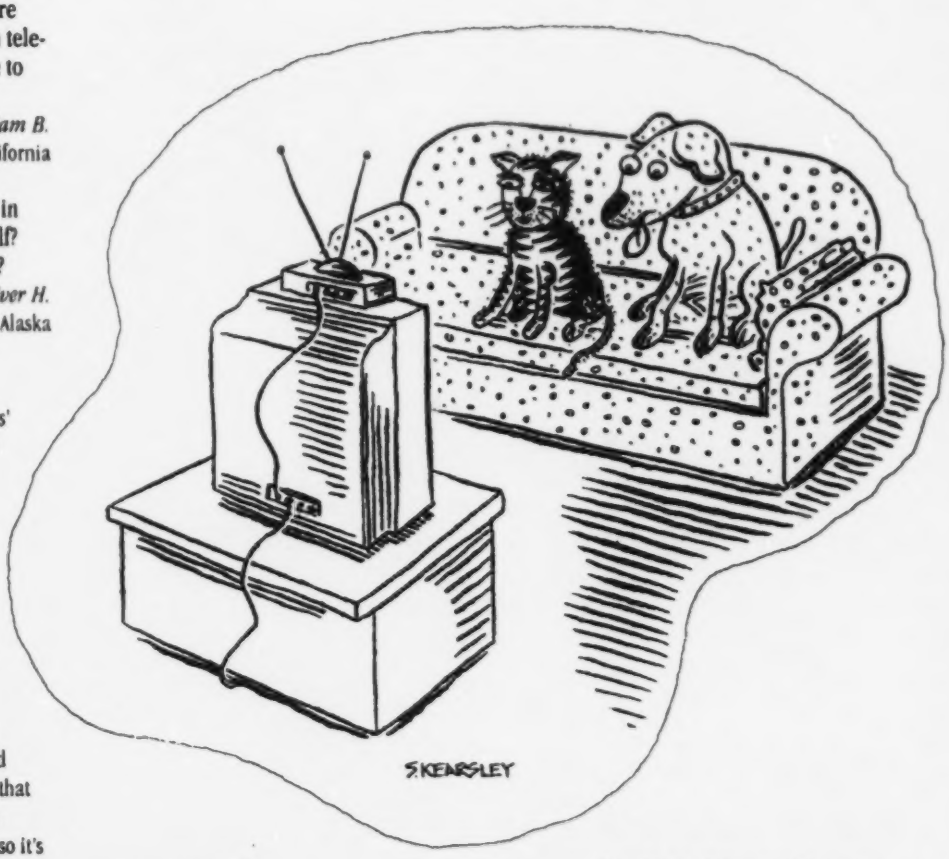
by Hugh McDonald

How is a dog's vision different from that of humans? My brother says that dogs are color-blind and can't see anything on television, but my dog sure seems to like to watch TV.

—William B.
San Francisco, California

My cat totally ignores his reflection in the mirror. Can he recognize himself? Can he even see his reflection at all?

—Oliver H.
Fairbanks, Alaska



Many people are interested in their pets' vision, but researchers can only infer how animals see from observing their behavior and studying their eyes and brains. And the huge variety of animal visual systems means that there are many ways of seeing the world. Let's look at some aspects of vision that researchers are pretty sure of, and then speculate on what might be happening in other situations.

People seem especially curious about their pets' color vision. Dogs are often said to be "color-blind," which might suggest that they see in black and white. But there are several different kinds of color blindness, so it's important to know which kind we're talking about.

The eyeballs of vertebrates (including dogs, cats, and humans) contain light-sensitive cells called rods and cones: Rods work in extremely dim light, but cones make color vision possible. Humans have three types of cones: Some respond to blue light wavelengths, some to green light, and some to red light. All the colors we see are produced by the combination of cones that respond to light reflected into our eyes. In color blindness, one or more cone system doesn't function normally. Red/green color blindness, an inability to distinguish between reds and greens, is most common. Blue/yellow color blindness, in which blues and yellows are perceived as the same, is rarer, and total color blindness is extremely uncommon.

What about dogs and cats? Research suggests that dogs have only two cone systems and see like people with red/green color blindness. A red ball on green grass would probably not stand out to a dog—both would be perceived as similar shades. There's more disagreement about cats: Some researchers argue that cats have three types of cones and see a range of colors comparable to those we perceive—but because their cones respond to different wavelengths of light then ours, they wouldn't see the *same* colors we do. Other researchers argue that cats have only two cone systems and have color vision like that of dogs. Further research might soon resolve this question.

Regardless of how dogs and cats see color, there's no reason why they shouldn't be able to see televised images—but they almost certainly don't perceive them as we do. The picture on your TV screen is actually a series of images presented in rapid succession. Our *persistence of vision*, a phenomenon that lets us hold onto an image for about a tenth of a second, combines these images into a smooth progression. But dogs and cats appear to be more sensitive to quickly flashing light than we are, so our pets' perceptions of television are probably dominated by flickering light.

Our pets should also be perfectly able to see reflections in mirrors. In fact, many dogs and cats play with reflections, but they often seem to ignore their *own*—and here's where we really start speculating, because researchers don't know why.

One theory is that household pets become accustomed to their own reflections early in life and stop finding them interesting, which explains why they play with novel reflections but not their own. Other researchers point out that reflections violate certain assumptions about real objects—they disappear at the mirror's edge, for example—so animals may ignore them because they don't seem real. It's also true that reflected images, unlike real objects, don't

stimulate senses other than sight. However, we should remember that we, too, generally ignore our own reflections—we really only pay attention to them when we're grooming. Since pets never use mirrors this way, it may only *seem* as if they're ignoring their own reflections.

There's a difference, however, between seeing yourself and *recognizing* yourself. Do animals recognize themselves? This question brings up difficult issues of consciousness and self-awareness. Some evidence suggests that only higher primates, such as chimpanzees and orangutans, recognize themselves in mirrors, which suggests that they're the only animals to have self-concepts (in addition, of course, to ourselves). That's controversial, but most researchers would agree that dogs and cats are unlikely to recognize their own reflections. In the end, though, we may never know exactly how other creatures experience the world—so this may remain an unsolved scientific mystery. 😐

If you're interested in learning more about animal vision, here are a few informative Web sites:

http://webexhibits.org/causesofcolor/17.html
http://www.sbnp.org/Wetlands/text/00-7-2-4.htm
http://www.animaleyecare.com/for.htm

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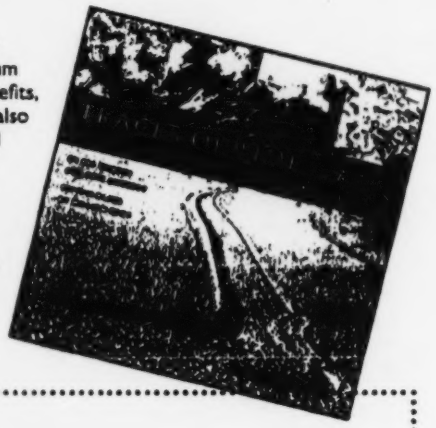

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Reviews & Resources

Tools & Toys

Robots are amongst us. What once seemed far-fetched, like something out of a cheesy sci-fi flick, has now become readily available, even commonplace. Today, robotic devices lend humankind a helping "hand" with everything from mowing the lawn to microsurgery (good luck trying to get that one past your HMO!).

Some say the day will come when robots take over the world. To this I say, "Good!" Since we mortals are the force behind robots, I'm confident that creators will refrain from using robots for destructive purposes. (Not that I know any personally, but I would think the truly evil creators would prefer to be more directly involved while wreaking havoc; it's more ego-boosting that way.) No, I think people will turn to robots for general time-saving activities, the more mundane the better. We'll continue to tell ourselves that, with all the time we're saving, we're finally free for noble, glorious pursuits. But who are we kidding? We're just going to end up snacking and watching a lot more bad television—except for those of us who are making robots.

Take Carlo Bertocchini of Belmont, California, for example. A mechanical designer by trade, Carlo's childhood love of tinkering with remote-controlled gizmos never left him. In the early '90s, he began attending monthly meetings of the San Francisco Robotics Society of America and entering robot sumo contests (both held at the Exploratorium; see page 14). Where did this all lead? Carlo is an international BattleBot champion (BattleBots are bruisin', handmade, robot "warriors" that duke it out with each other—often to the death—all to the delight of a cheering, bolt-thirsty mob). His creation? The infamous "BioHazard," star of small screen and large arena.

By now, you're probably anxious to get started with your own robotic creation. Look no further than our own Exploratorium Store.

A good, basic, ready-to-go robot is the **Climbatron ($11.50)**. I have one myself (okay, it's my son's, but he lets me play with it), and I highly recommend it. As the name implies, Climbatron climbs up. It climbs down. It goes upside down. It attaches to windows, or it just walks somewhere. Why not spice up the office routine and have Climbatron deliver your memos in style?

Kids (ages 6+) will enjoy Sonic Robot **($52.90)**, motorized, sound-producing robots they can build themselves. Gears! Small pieces! Noise! What could be better? Why, dinosaurs, of course. And **Robotix ($12.50)** is just what the mad scientist ordered for some prehistoric motorized action.

Older budding robotists will enjoy the **Robotics and Robotikits series ($29.95 and up)**. Designed for ages 10+ (you would be included in the +, so go on, you know you want one), there are many varieties to pick from including Soccer Robot, Rockit Robot, Moon Walker, Solar Car, and Hyper Peppy, which reacts to sound (I'm going to have to pass on that one; I've got too many Hyper Peppies at home already).

The **Monit 965 WA011 ($119.95)** provides for more advanced robotics. This is a 4-bit microcomputer that hooks up to your PC. It moves, writes, and gets jiggy with its bad self (translation: It can dance), all according to an individualized program that you design. An optional interface card is available so your more socially inclined robots can communicate with other computers.

And finally, for all you dreamers out there, the ultimate robot book of books, one no robot aficionado should be without: ***Robo sapiens: Evolution of a New Species*** **($29.95)** by Peter Menzel & Faith D'Aluisio, published by MIT Press, 2000. Not content to act as a comprehensive account of the field of robotics (the glossary is the most complete I've ever seen), this gorgeous, generously sized book delves into the mind-blowing realm of a cosmic question: Could machines and humankind meld into a single species? Not quite ready to go there yet? Me neither. I was just happy to marvel over the pictures. The photography in this book is excellent beyond words.

Go forth with your tools and toys. Create your own super robotic race. Become master of your own world. Do good.

—Ellen Macaulay

All products are available from the Exploratorium Store, where you can shop in person, or order by phone at 415/561-0393. Exploratorium Members always get a 15-percent discount. For membership information, call 415/561-0302. Prices and availability are subject to change.

Related Reading

Robots at Work by Jake Widman

For more information on the use of robots at the World Trade Center disaster, point your browser to the National Science Foundation Web site at http://www.nsf.gov/od/lpa/news/press/01/pr0178.htm and The Center for Robot-Assisted Search and Rescue at http://www.crasar.org.

For a general overview of robots in industry and science, check out *The Usborne Introduction to Robotics* by Tony Potter and Ivor Guild. London: Usborne Publishing Ltd., 1993. This informative book shows how robots are designed to perform difficult and dangerous tasks with remarkable efficiency. The book's colorful diagrams are entertaining for younger readers, but its strikingly in-depth explanations make it appropriate for all ages.

The Robot in the Mirror by Hugh McDonald

Want to learn more about robots in film and television? Here are a few Web sites to get you started:
http://www.cinema-sites.com/
http://www.mdle.com/ClassicFilms/FeaturedVideo/video179.htm
http://www.chaoskids.com/ROBOTS/directory.html
http://www.lostinspace.tv.com

Race for the RoboCup by Beth Martin

For information about past and future robot soccer events, see RoboCup's official Web site at www.robocup.org. Also, see the CS-Freiburg robotic soccer team's site at www.cs-freiburg.de

Bringing Up Baby by Erica Klarreich

For more information about SAIL, plus extensive links to related topics, see Juyang Weng's homepage: www.cse.msu.edu/~weng/index.html.

Ars Robotica by Lisa Pine

For more information about the artists featured in this story—including more photos of their work—see their Web sites:
Chico MacMurtrie: www.cronos.net/~bk/amorphic
Stelarc: www.stelarc.va.com.au
Nicholas Anatol Baginsky: www.provi.de/~nab
Ken Rinaldo: www.ylem.org/artists/krinaldo/index.html
Ullanta Performance Group: www-robotics.usc.edu/~barry/ullanta
Adrianne Wortzell: www.artnetweb.com/wortzel

Inside the Mind of a Robot Builder by Steve Kearsley

Want to learn to make your own robot? *The Robot Builder's Bonanza*, by Gordon McComb (McGraw-Hill, 2001), robot building from the simple to the complex. Or check out the San Francisco Robotics Society of America's Web site: http://www.robots.org.

Credits & Acknowledgments

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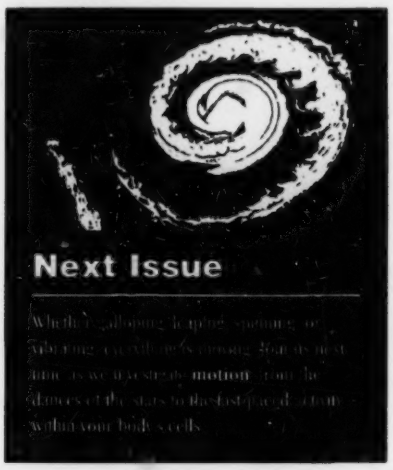

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Errata

Vol. 25, No. 2 (*Water*): In "Water: The Liquid of Life," page 8, it says "Because of its capacity to bond with hydrogen, water has a very high specific heat." The text should read "Because of its capacity for hydrogen bonding, . . ." which means that the positively charged hydrogen atoms in one water molecule are attracted to negatively charged oxygen atoms in other water molecules.

Vol. 25, No. 3 (*Coffee & Tea*): The timeline on page 11 attributes the first greenhouse to Louis XIV of France. In fact, sheets of mica tented over fragile seedlings were probably the first "greenhouses." Louis's, though, was one of the earliest structures we'd recognize as a modern-style greenhouse, with sloping glass walls and a system of vents to control the internal temperature.

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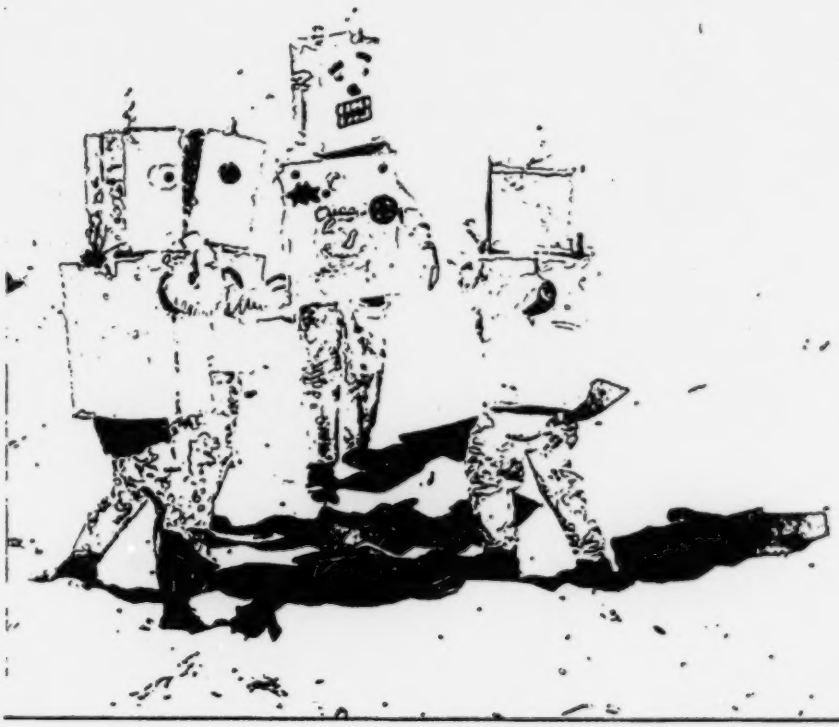

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